The MODIS Operational Cloud Products: Data Sets, Algorithms, and Examples

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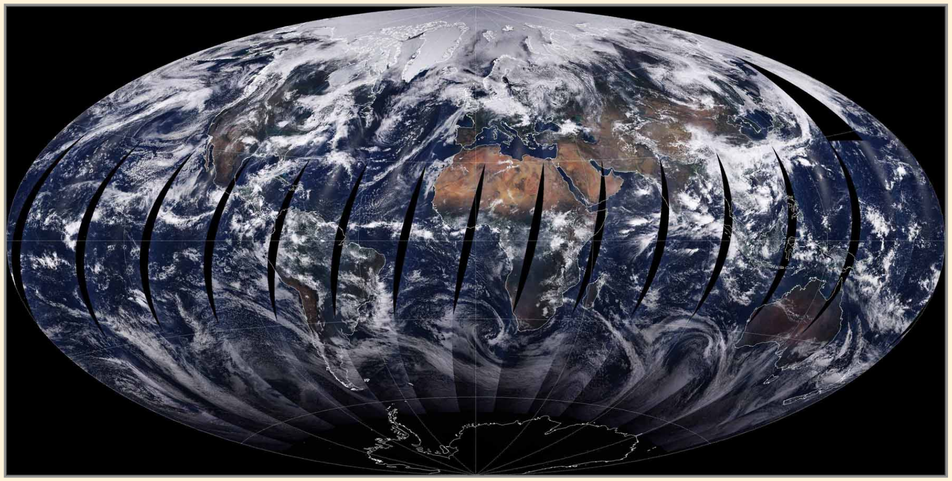


MODIS true-color daily composite

Outline

- Perspective: Why clouds? What can we infer from satellites?
- Overview MODIS cloud products
- Cloud detection and height retrievals
- Cloud optical and microphysical retrievals and examples (Level-2, -3) from the Collection 5 algorithm

When it comes to using remote sensing data (or any data), a little bit of knowledge can be a dangerous thing!

– *ask questions*

Why Cloud Observations?

There are a number of fundamental reasons:

- Establishing climate quality data records
- Radiation budget studies (e.g., CERES/MODIS/GEO)
- Water budget/cycle studies (e.g., role of ice clouds and convection in UTH)
- Establishing data sets for climate and weather forecast validation, and model parameterization development
- Data assimilations
- Cloud process studies, including aerosol-cloud interactions
- Atmospheric chemistry (effect on photochemistry, *Liu et al.*, *2006*)

Cloud Products and Techniques

- **Cloud detection/masking**
  - Multispectral and/or multiview imagers with appropriate spatial resolution, lidar, radar
- **Cloud thermodynamic phase**
  - Multispectral imagers w/SWIR and/or IR (8.5 μm) bands, polarimeters w/ multiangular views and good spatial resolution, lidars w/depolarizaton capability
- **Cloud top properties**: pressure, temperature, effective emissivity
  - Multispectral and/or multiview imagers (thermal window, CO_2 bands, other gas absorbing bands), UV imagers, polarimeters
- **Cloud optical & microphysical properties:** optical thickness, τ, effective particle size, r_e, water path
  - Solar reflectance imagers (r_e from 1.6, 2.1, 3.7 μm bands)
  - IR imager and sounder retrievals of τ, r_e for thin clouds
  - Polarimeter w/multiangular views (r_e)
  - Microwave radiometers (water path)

Cloud Products and Techniques, cont.

- **Cloud vertical structure: geometric information & optical/ microphysical properties**
  - Radar (water content profile), lidar (extinction profile)
- **Drizzle detection and precipitation**
  - Radar, microwave imagers

Summary of MODIS Operational Cloud Products

- Pixel level products (Level-2)

MOD35, MYD35

  - Cloud mask. *S. Ackerman, R. Frey, U. Wisconsin/CIMSS*

    1km, 48-bit mask/11 spectral tests, clear sky confidence in bits 1,2

MOD06, MYD06

  - Cloud top properties: pressure, temperature, effective emissivity. *P. Menzel, R. Frey, NOAA-NESDIS & U. Wisconsin/CIMSS*

    5 km, CO_2 slicing for high clouds, 11 μm for low clouds
  - Cloud optical & microphysical properties**:** optical thickness, τ, effective particle size, r_e, water path, thermodynamic phase. Primary r_e from 2.1 μm band. *M. D. King, S. Platnick, GSFC*
  - IR-derived thermodynamic phase. *B. Baum, U. Wisconsin/SSEC*, SDS name **Cloud_Phase_Infrared** (day, night, and combined)
  - Cirrus reflectance (via 1.38 μm band). *B.-C. Gao, Naval Res. Lab*, SDS name **Cirrus_Reflectance**

- Gridded & time-averaged products (Level-3): statistics, histograms, contains all atmosphere products (clouds, aerosol, clear sky aggregations)

Some things to Ponder

Some cloud retrievals considered basic and fundamental are ill-defined

- What is a cloud mask? What is a cloud (depends on the part of the spectrum, among other things)? Cloud phase? Cloud-top height (radar vs. lidar vs. IR vs. polarization)? Cloud effective particle size (local quantity, not vertically integrated as with τ)?

What Do We Mean by a Cloud Detection?

What is a cloud? It depends! What is considered a cloud in some applications may be defined as clear in other applications.

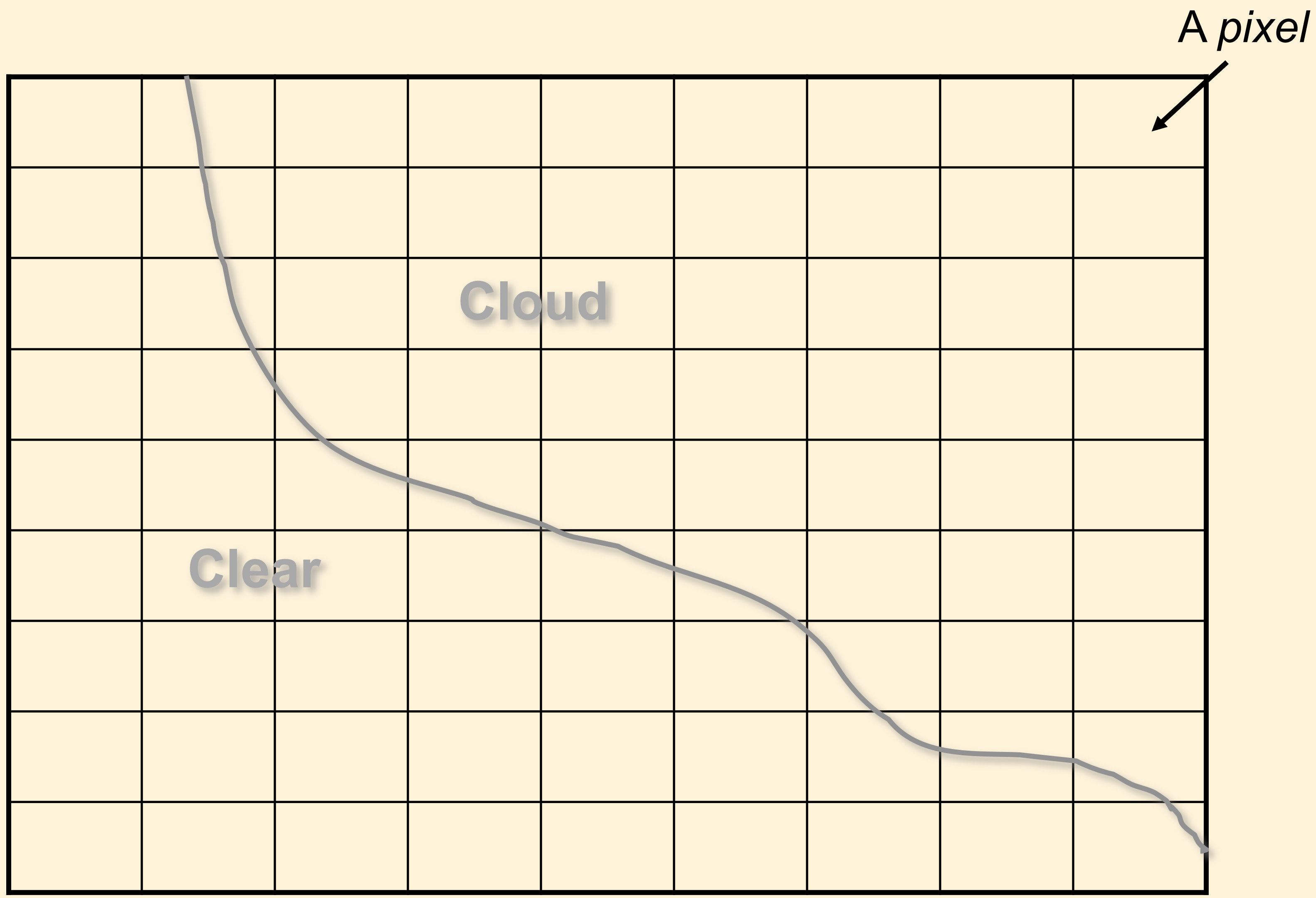
Detection of clouds is also a function of instrument capability and algorithm design. Cloud detection is a function of contrast between the target (e.g. cloud) and the background. Contrast can be:

Spatial: Large FOVs are generally more uniform lowering contrast.

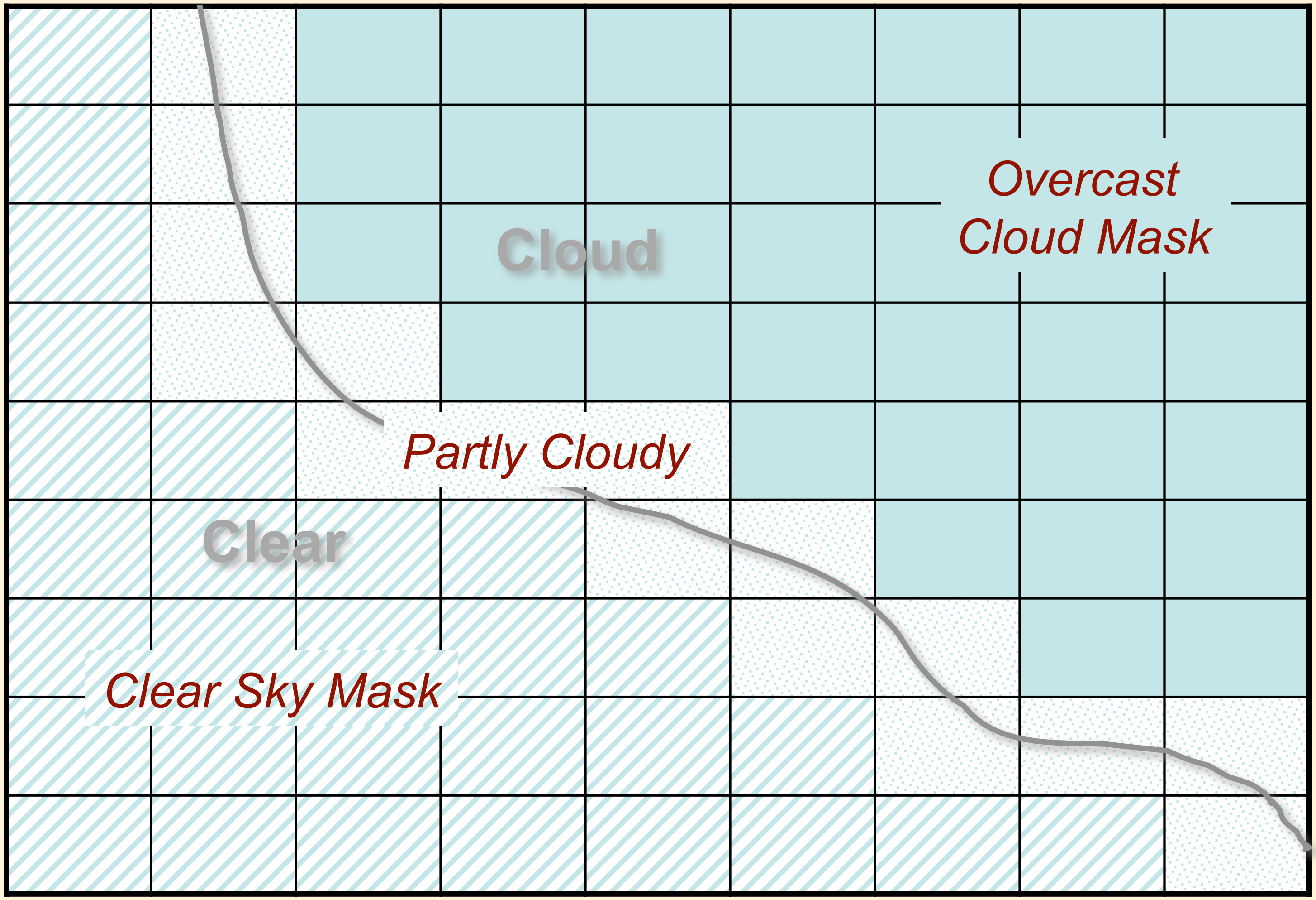
Temporal: Clouds can be detected in a sequence of images if the clouds are moving.

Spectral: Spectral contrast is determined by the radiative properties of the cloud and surface.

What Do We Mean by a Cloud Mask?

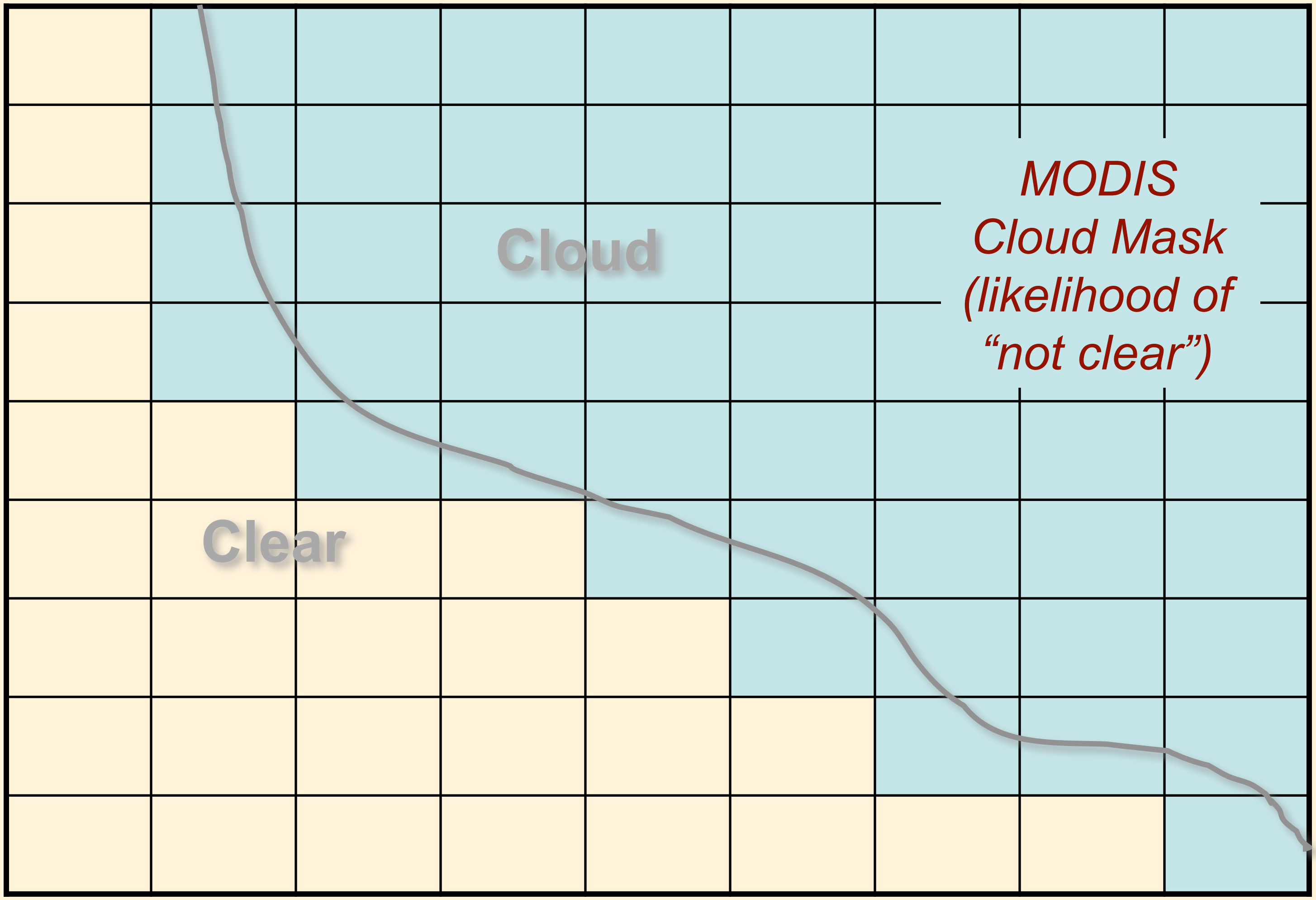


What Do We Mean by a Cloud Mask?

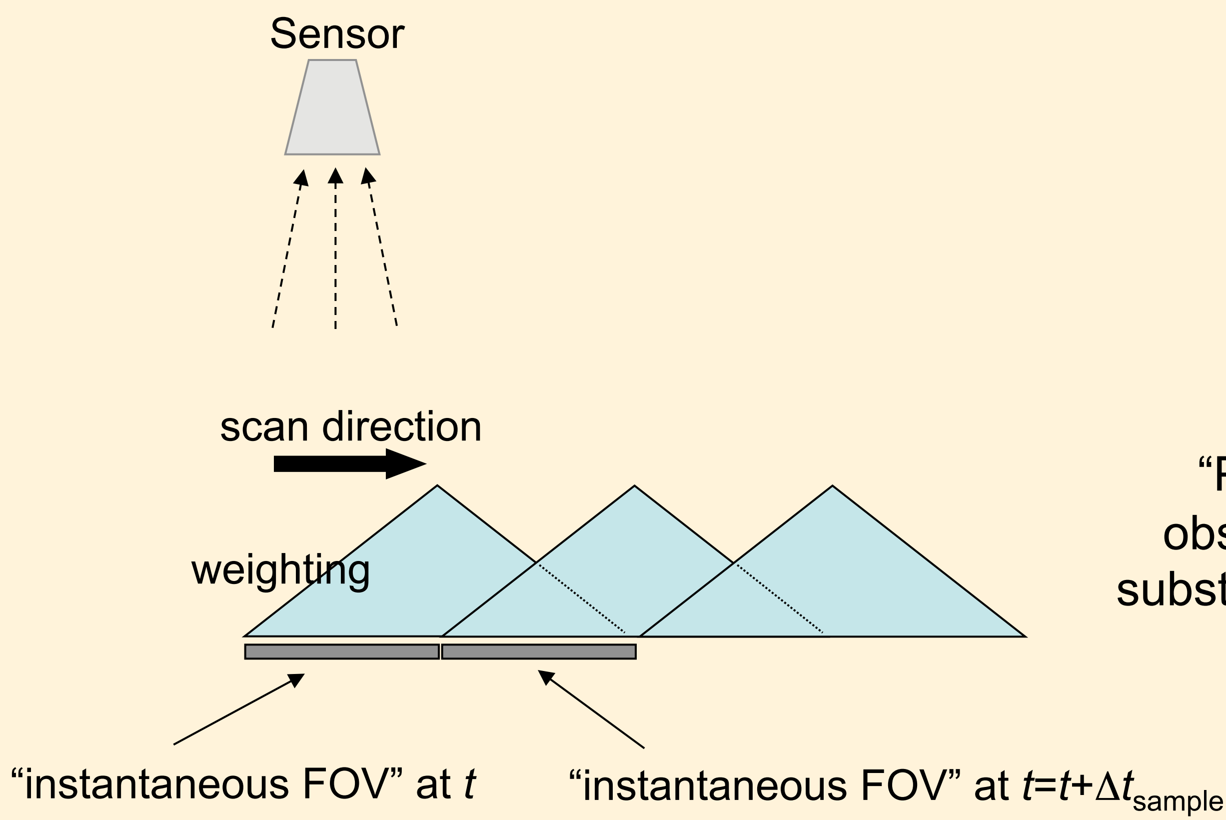


What Do We Mean by a Cloud Mask?

Most cloud masks are Clear Sky Masks



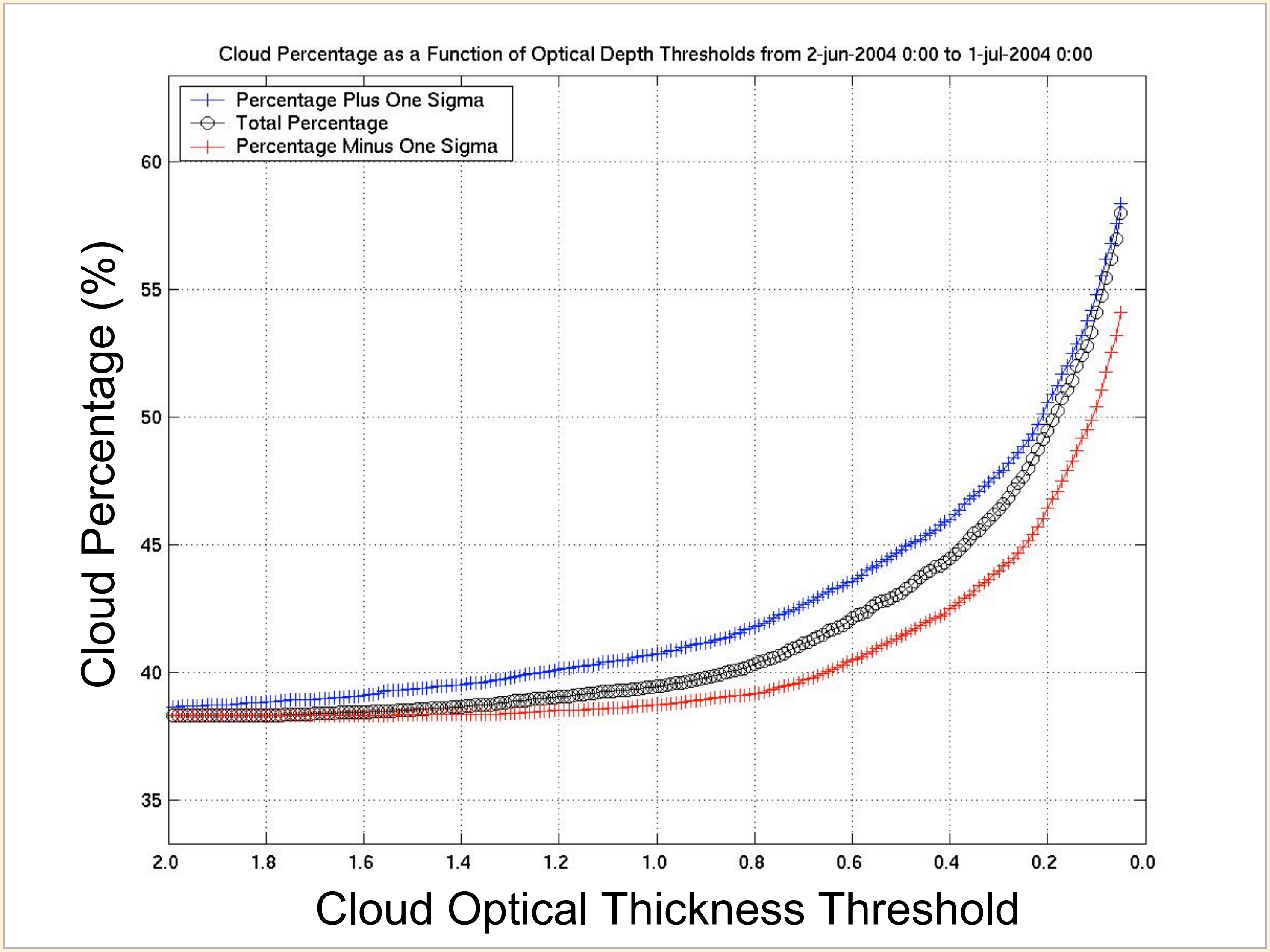
Another Issue: What is a Pixel?



“Pixels” (individual observations) overlap substantially in the across-track direction

Moral of this story: what a mask is “masking” and what is meant by a “pixel” needs to be appreciated before worrying about the spectral and/or spatial information used in the mask.

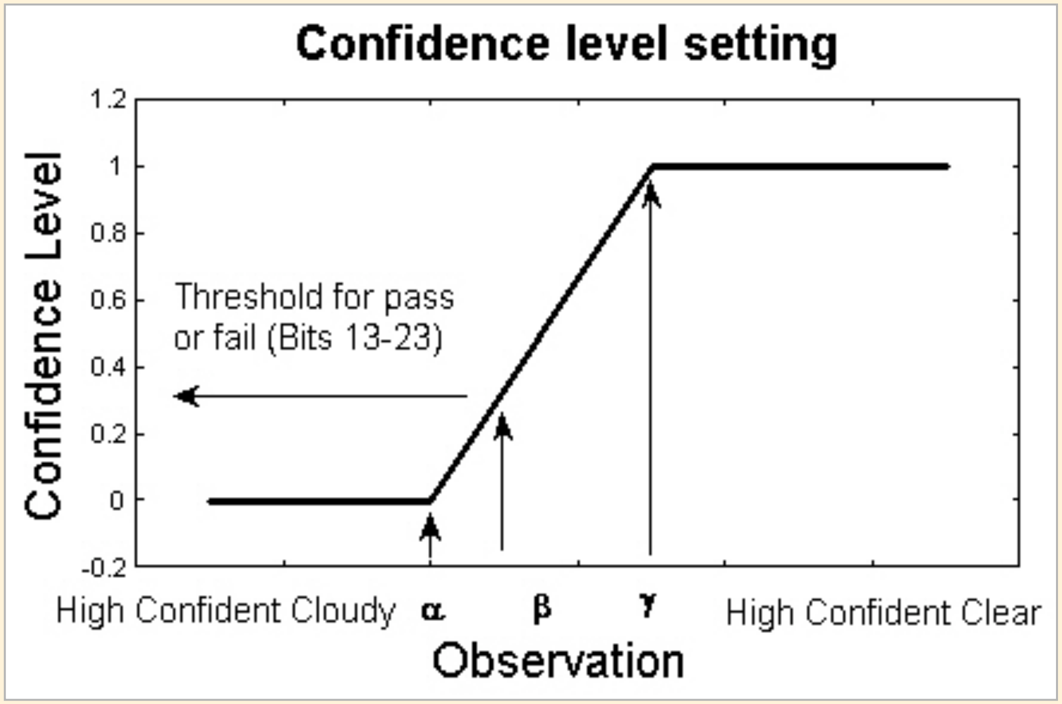
Cloud amount depends on detection capability



The total detected cloud fraction is a function of cloud τ sensitivity

MODIS Cloud Detection

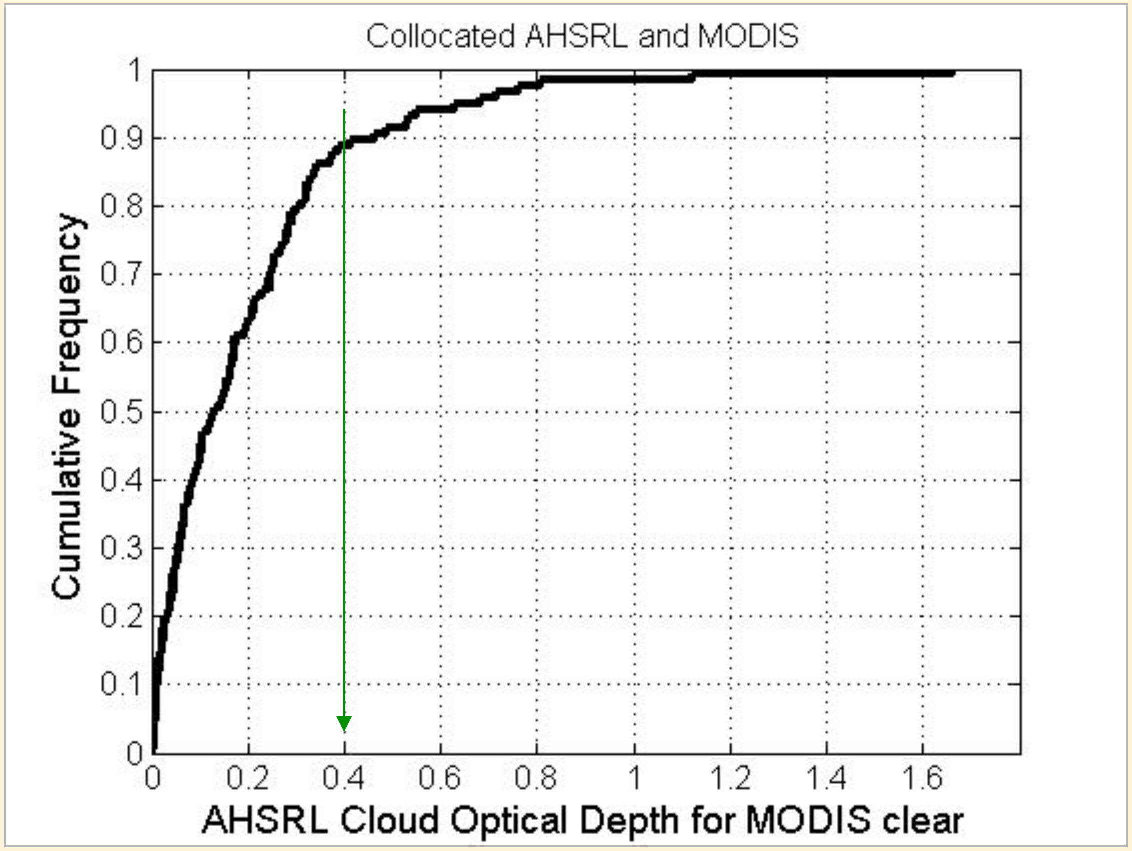
Cloud Mask Quality Flags



- Each test returns a confidence (F) ranging from 0 to 1.
- Similar tests are grouped and minimum confidence selected [min (F_i)]
- Four values; 0, >.66, >.95 and >.99

Quality flag defined as: $Q = \sqrt[N]{\prod_{i=1}^{N} \min(F_i)}$

What is a cloud?



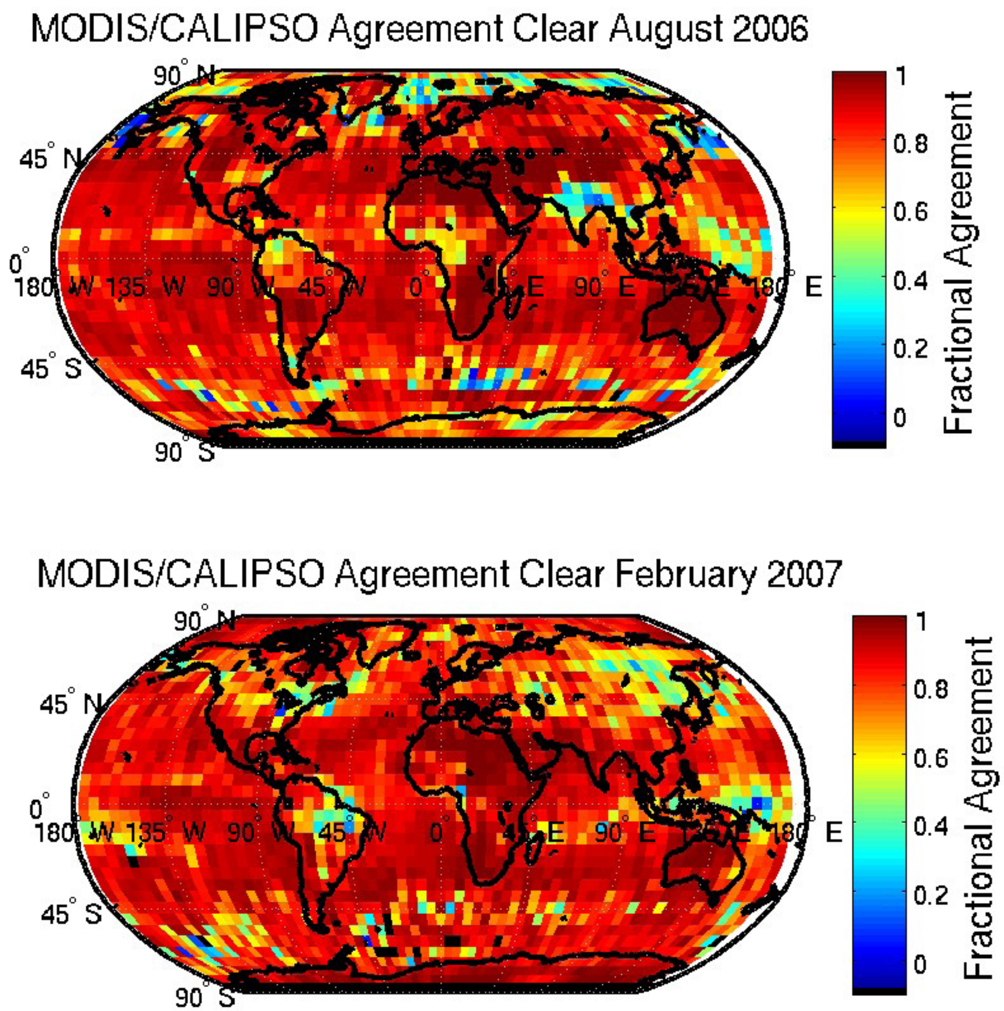
Cloud τ threshold over land for Eloranta ground-based “Arctic” HSRL (a direct meas. of τ)

MOD35 (Cloud Mask) Algorithm & C5 Changes

(S. A. Ackerman, R. Frey)

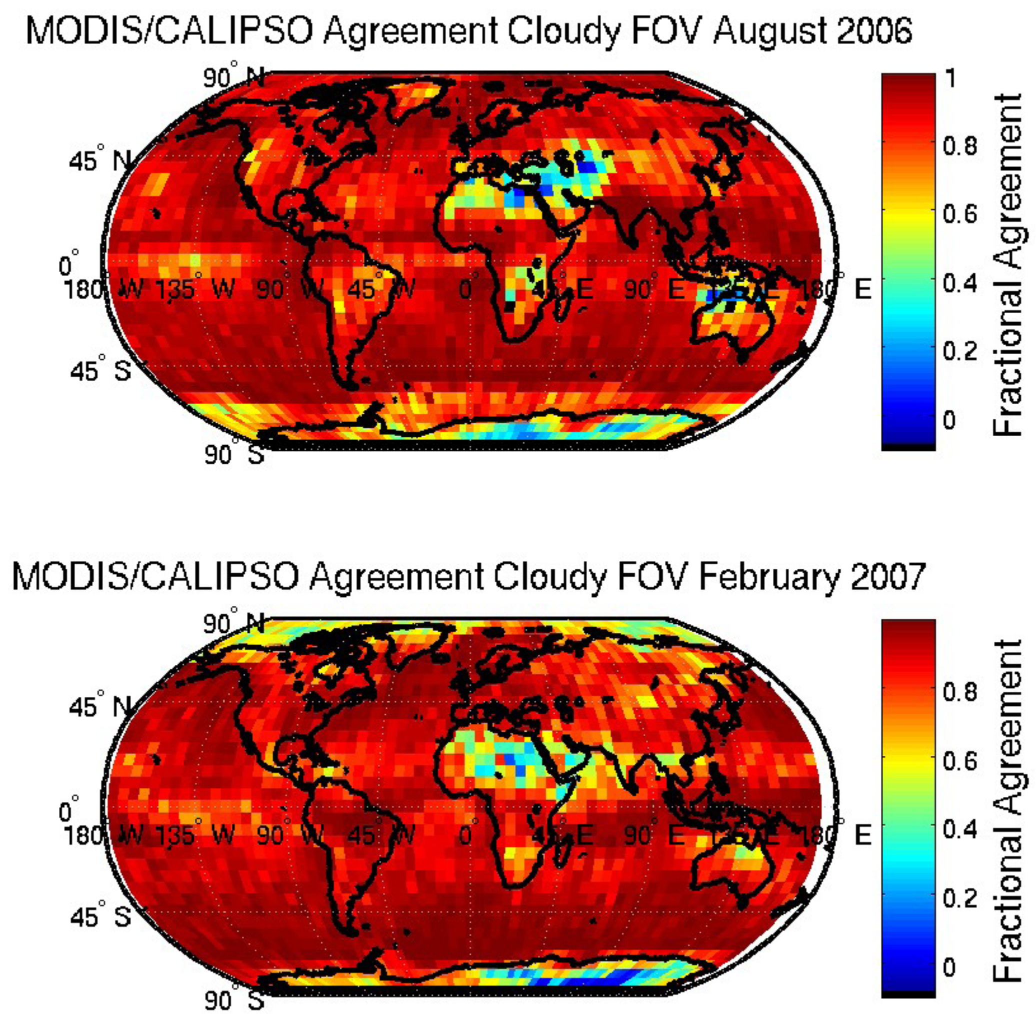
- MOD35/MYD35
  - C5 Nighttime: less nighttime ocean clouds (less aggressive variability test), now using of Reynolds SST
  - C5 Polar night: more clouds (7.3-11 μm test)
  - C5 Polar day: reduces cloud fraction, e.g., Greenland, Antarctica (3.9-11 μm test)
  - C5 Land night: using GDAS T_{sfc}
  - C5 Ocean day: detect more small trade Cu (0.86 μm test), though more dust as cloud
  - Detection limit for cirrus corresponds to optical thickness ~ 0.2-0.3

Differences in clear-sky detection



Holz et al., 2008

Differences in cloudy-sky detection



Holz et al., 2008

MOD06 Cloud-Top Property Retrievals & C5 Changes

(P. Menzel, S. A. Ackerman, R. Frey)

- MOD06/MYD06 Cloud-Top Properties

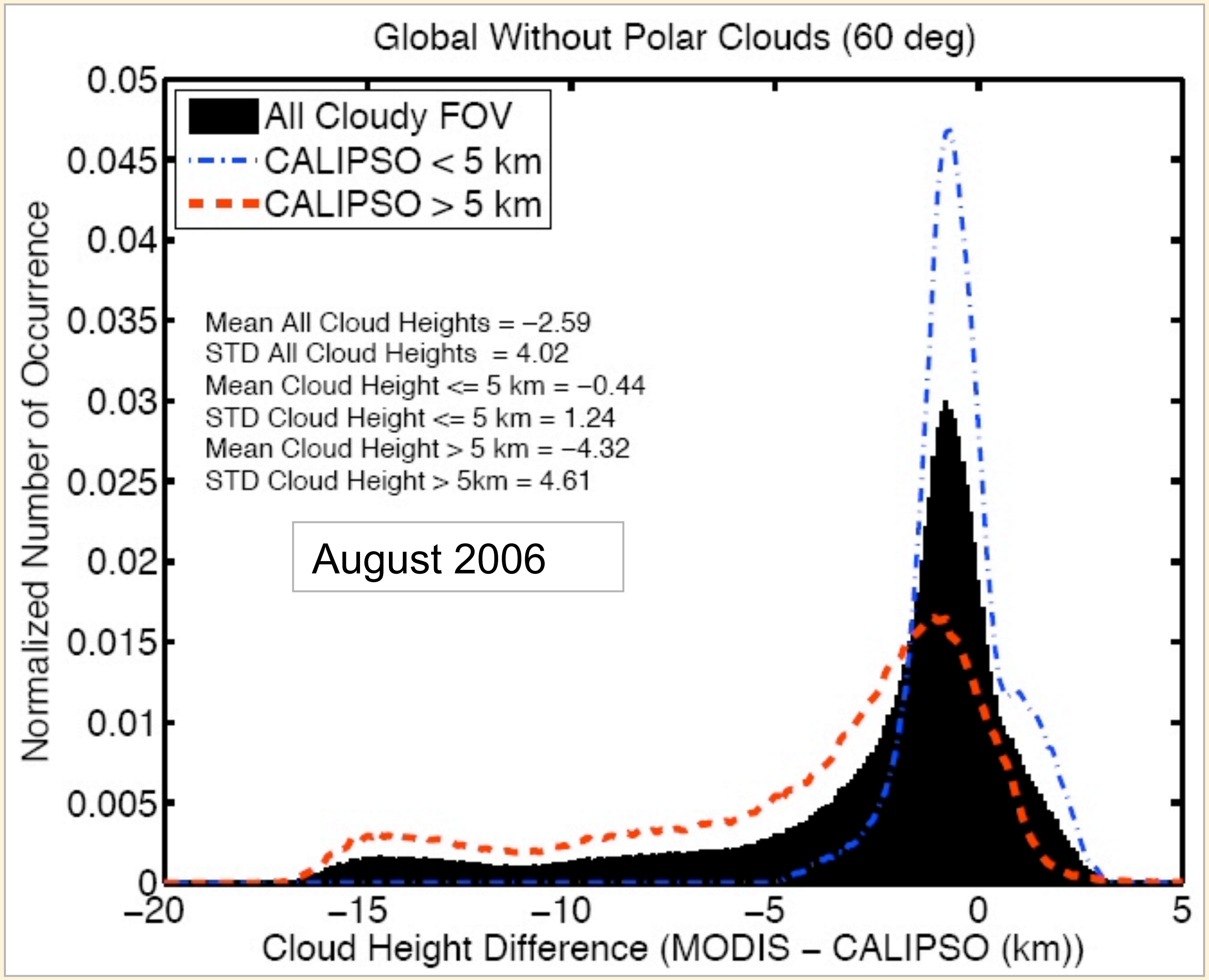
  SDSs: **Cloud_Top_Pressure**, **Cloud_Top_Temperature, Cloud_Effective_Emissivity,** et. al – day, night and combined

  C5 has empirical radiometric bias corrections for the CO_2 bands, giving more accurate CO_2 slicing retrievals

  Known Issues: Low clouds (thermal window retrieval) can have low pressure bias in strong inversions (e.g., marine Sc), biases from multilayer cloud scenes, …

Differences in cloud height

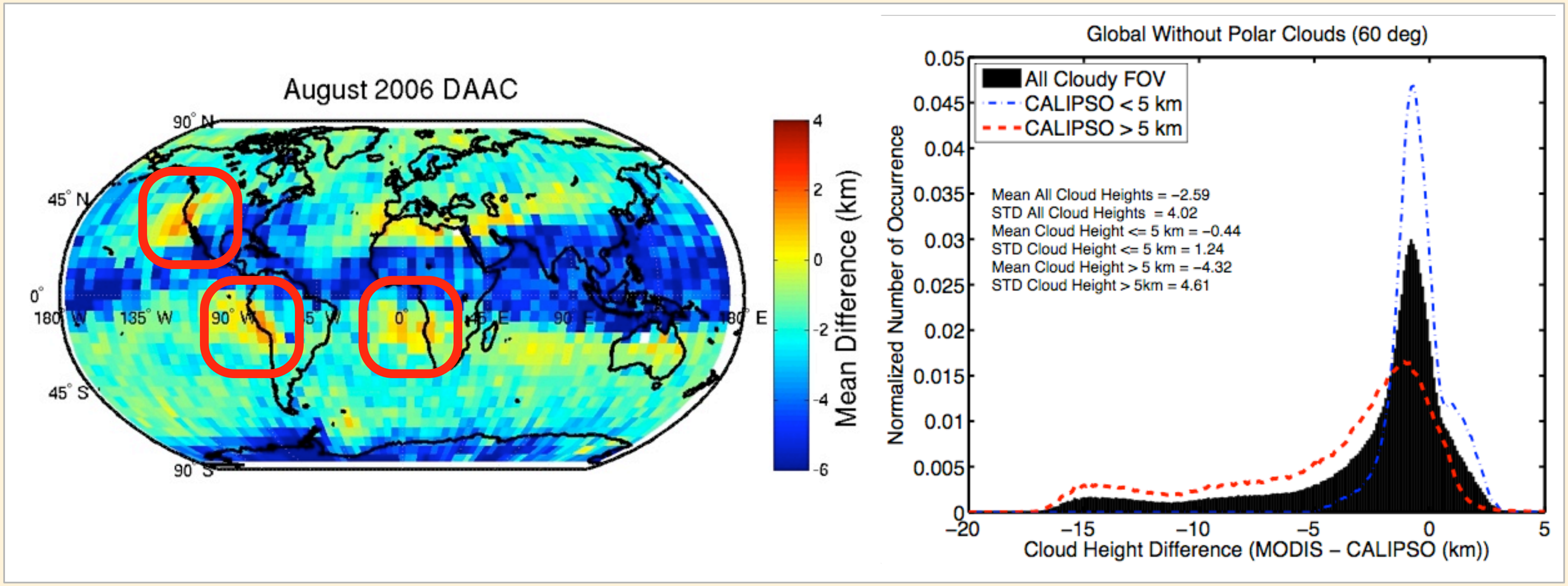
Derived cloud top altitude comparison



As expected, for thin clouds, the MODIS (IR passive approach) is sensitive to a layer below the physical cloud top.

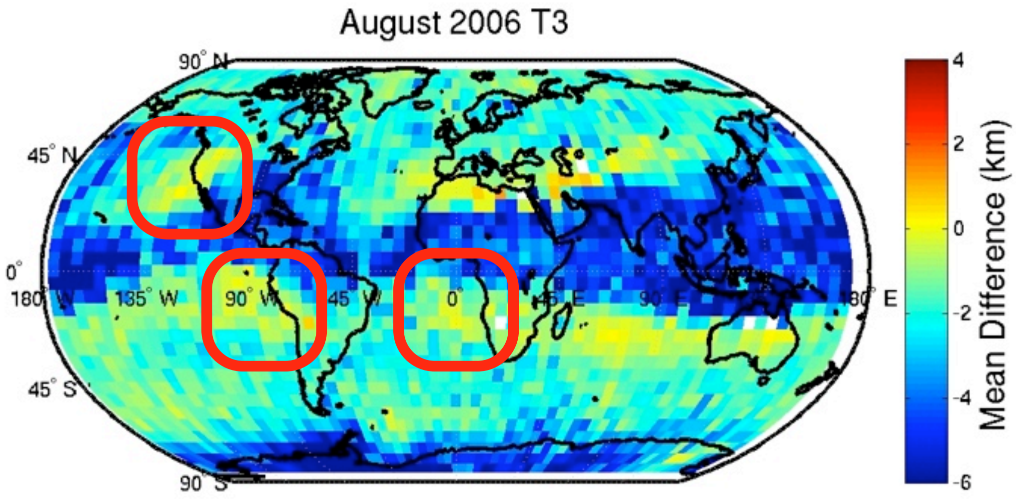
Differences in cloud height

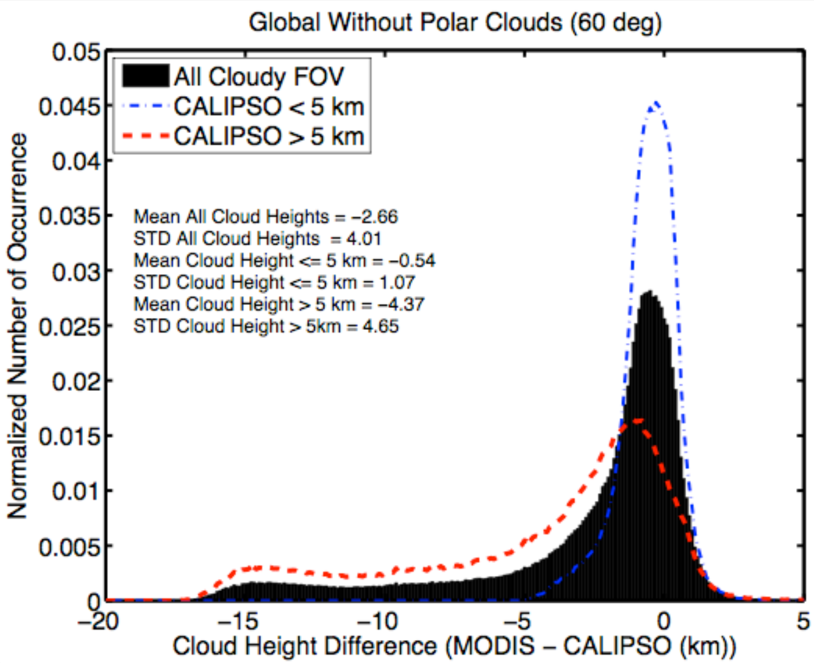
MODIS Marine Stratus Cloud Height Over-Estimation found and fixed



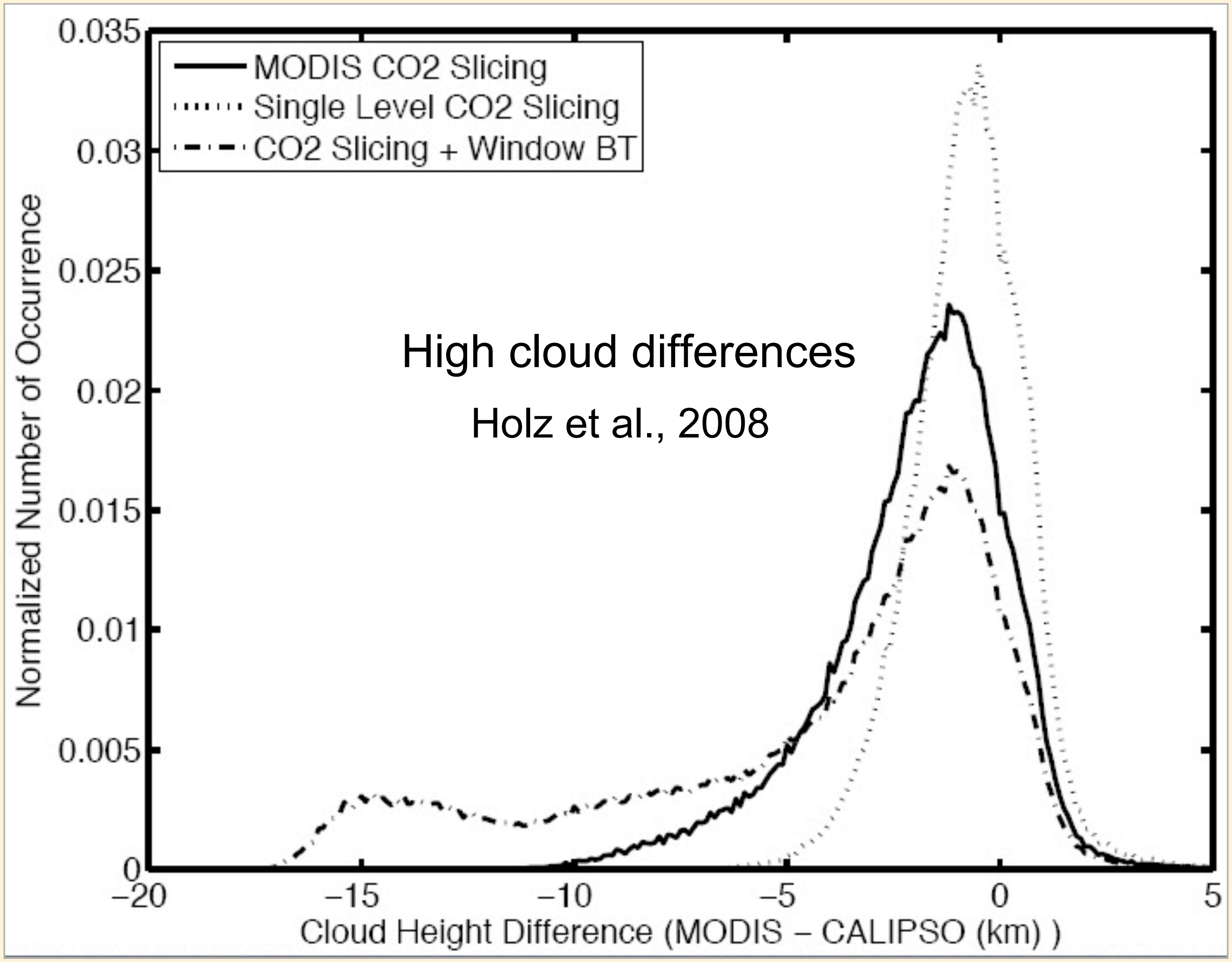
Differences in cloud height

MODIS Marine Stratus Cloud Height Over-Estimation found and fixed (Minnis et al. approach)



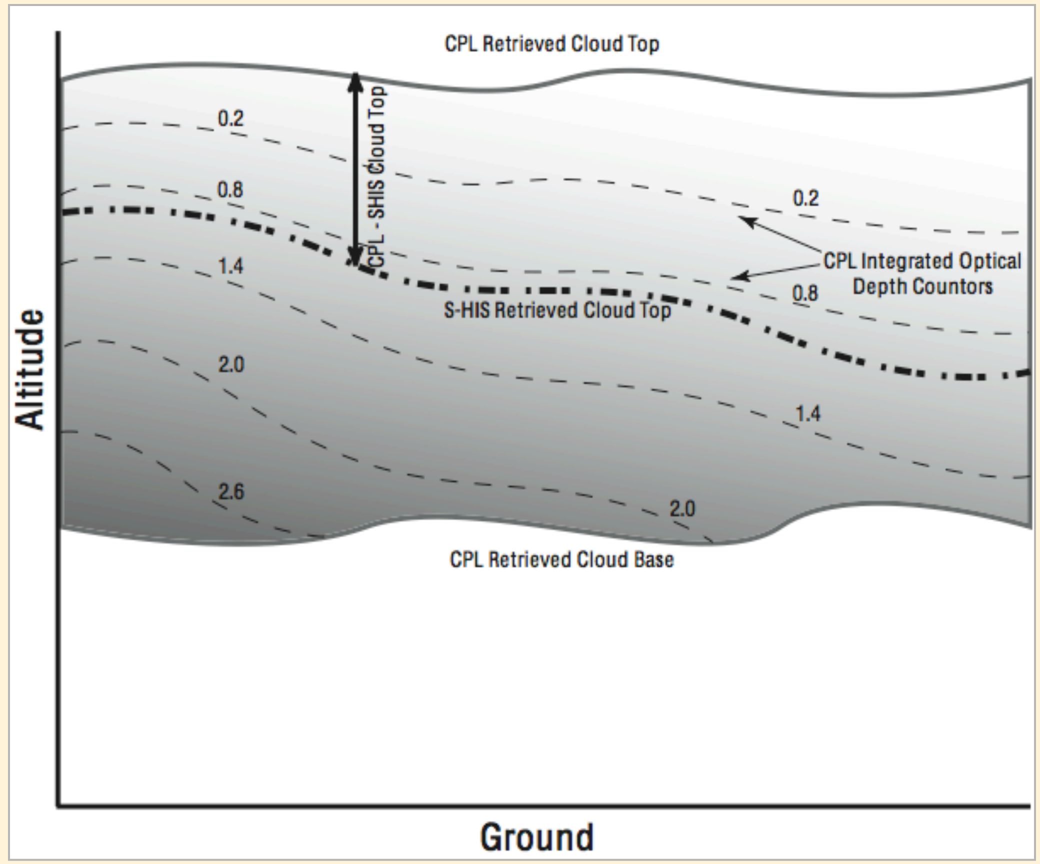


Differences in high (CALIOP>5 km) cloud height



Some differences in cloud height expected

A schematic of the lidar integrated cloud optical depth at the level of the passive IR cloud top retrieval.



Holz et al., 2006

MODIS Cloud Optical, Microphysical Product: MOD06

(M. D. King, S. Platnick, J. Riedi, G. Wind, B. Wind, E. Moody, M. Gray, P. Yang, et al.)

- Optical thickness (τ_c), effective particle radius (r_e), water path, phase (**Cloud_Phase_Optical_Properties**)
- 1 km spatial resolution, daytime only, liquid water & ice clouds
- Global: retrievals over land, ocean, and snow/sea ice surfaces
- 2-channel solar reflectance algorithm
  - standard retrievals
    - 1 non-absorbing band: 0.65 (land), 0.86 (ocean), 1.2 µm (snow/ice) + each of following absorbing bands: 1.6, 2.1, 3.7 µm => 1 τ, 3 r_e retrievals
    - 2.1 µm combination is the "primary" retrieval (**Cloud_Optical_Thickness**, **Cloud_Effective_Radius**, **Cloud_Water_Path**)
    - r_e from other absorbing bands given as differences (**Effective_Radius_Difference**)
  - 1.6, 2.1 µm band combination used over snow/ice and water surfaces (SDS names: ***_1621**)
- Ancillary data: cloud mask, cloud-top pressure/temperature, NCEP GDAS, global spectral albedo maps, snow/ice maps, …

Optical/Microphysical Retrieval Issues

Critical issues (especially for global processing):

- To retrieve or not to retrieve?
- Cloud thermodynamic phase: liquid water or ice libraries?
- Ice cloud models.
- Multilayer/multiphase scenes: detectable?
- Surface spectral albedo, including ancillary information regarding snow/ice extent.
- Atmospheric correction: requires cloud top pressure, ancillary information regarding atmospheric moisture & temperature profiles.
- Cloud-top temperature, ancillary surface temperature: needed for 3.7 μm emission (band contains solar and emissive radiance).
- 3D cloud effects.

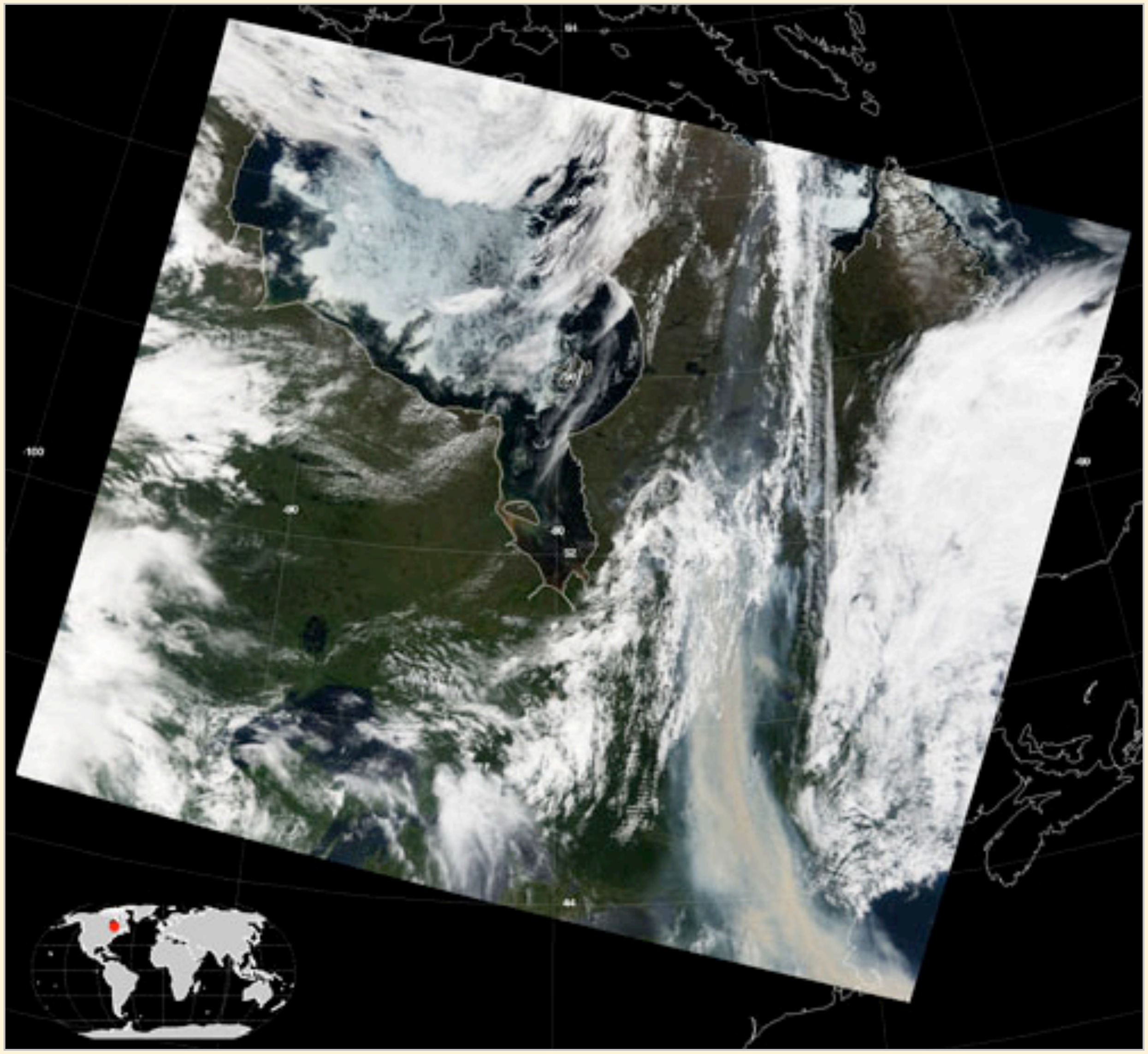
Some MOD06 Optical/Microphysical Collection 5 Changes

(http://modis-atmos.gsfc.nasa.gov/products_C005update.html)

- New “Clear Sky Restoral” algorithm implemented after cloud mask (to identify pixels incorrectly identified as cloud or partly-cloudy pixels).
- Updated cloud phase algorithm (still a difficult problem)!
- New ice cloud models (Baum et al. 2005).
- New research-level multilayer cloud flag. Level-3 code separately aggregates single layer and multilayer cloud fraction, as well as single layer retrievals.
- New MODIS-derived global snow-free land surface spectral albedo maps; snow/ice spectral albedo maps for Antarctica, Greenland; hemispheric average ecosystem-based snow/ice albedo over land and for sea ice; new IGBP ecosystem map. *Available for download on Atmosphere team web site.*
- New 1.6-2.1 μm retrievals over ocean and snow/ice surfaces.
- New pixel-level τ, r_e, *WP* retrieval uncertainties (baseline) and estimates of uncertainty of L3 means.

Example MODIS Data Granule

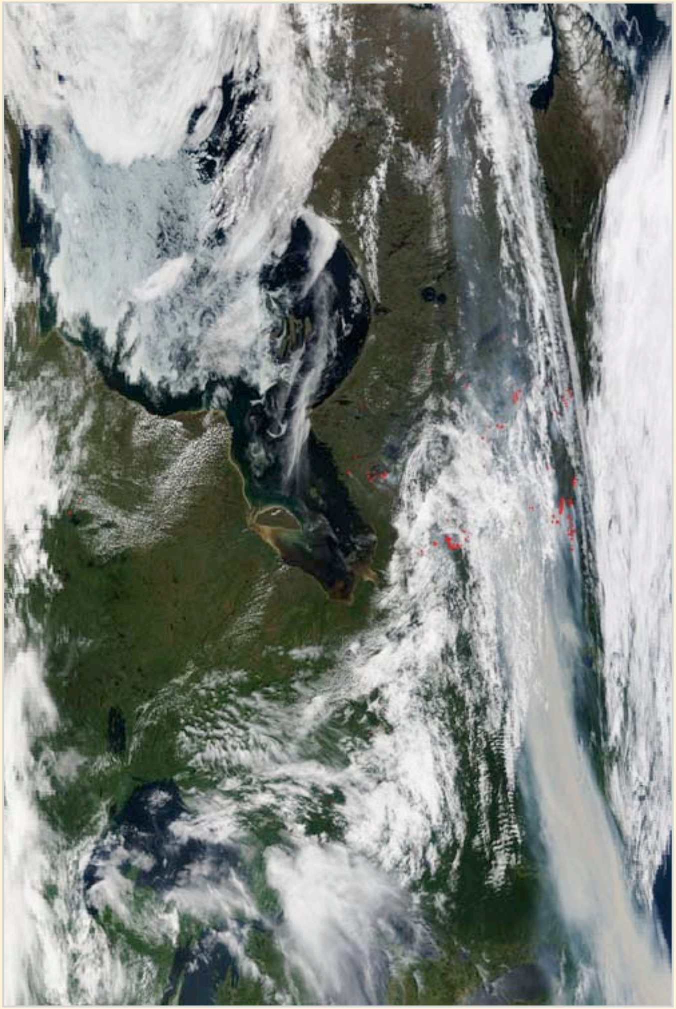
Canadian Fires, MODIS Terra, 7 July 2002



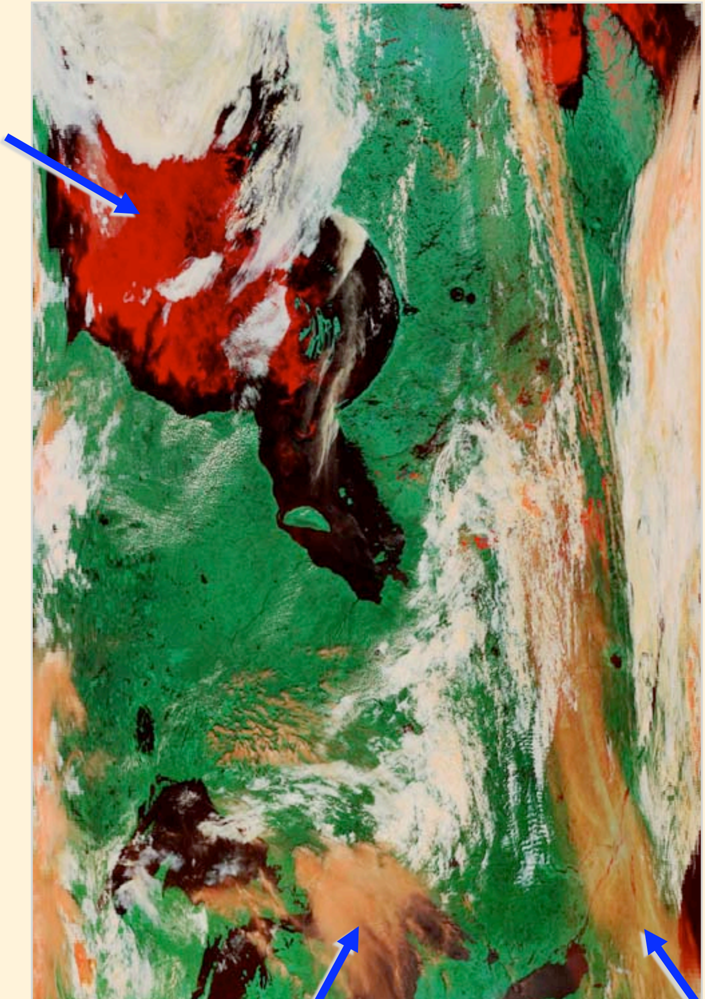
Example MODIS Data Granule

Canadian Fires, MODIS Terra, 7 July 2002

true color



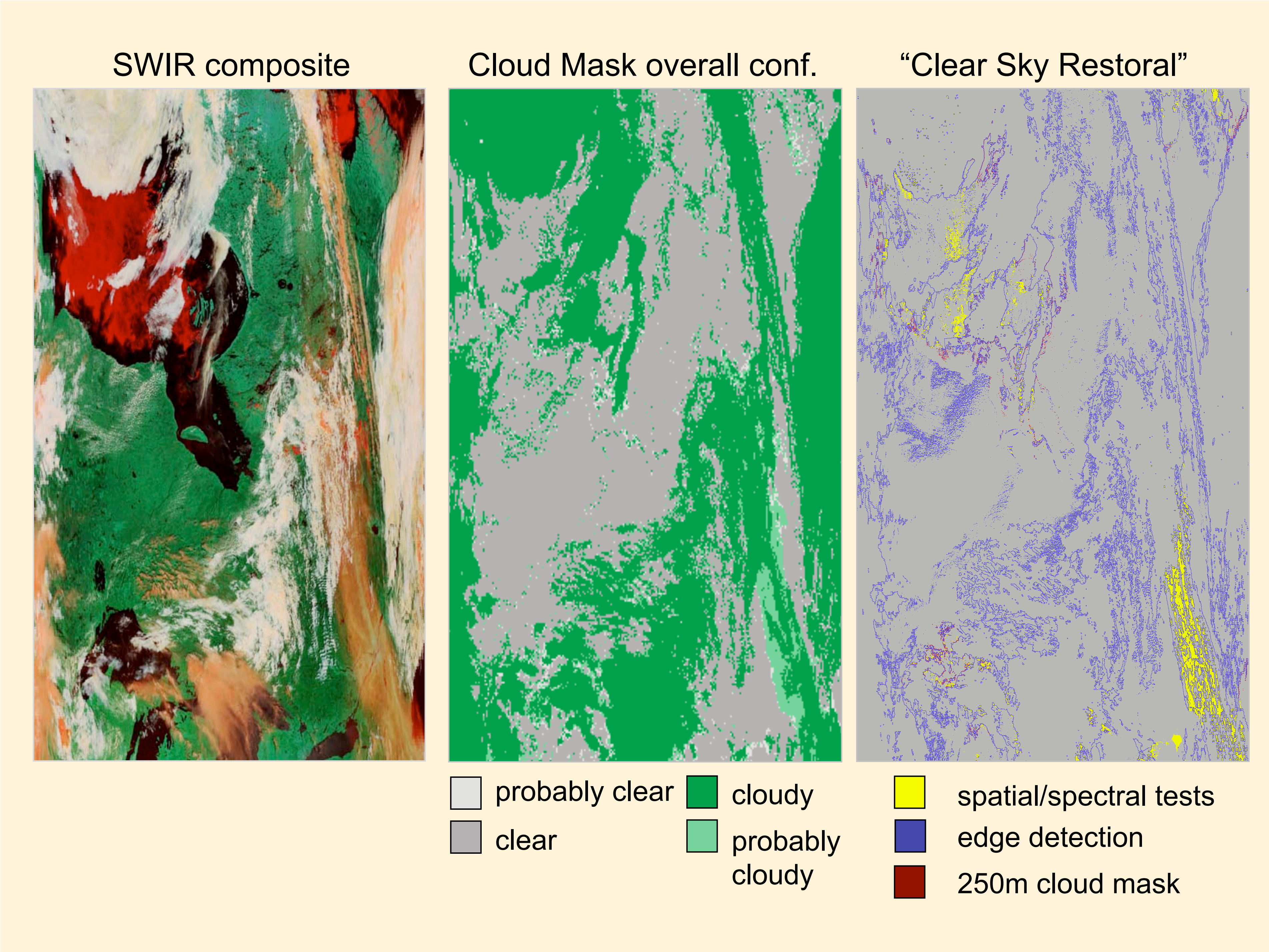
SWIR composite

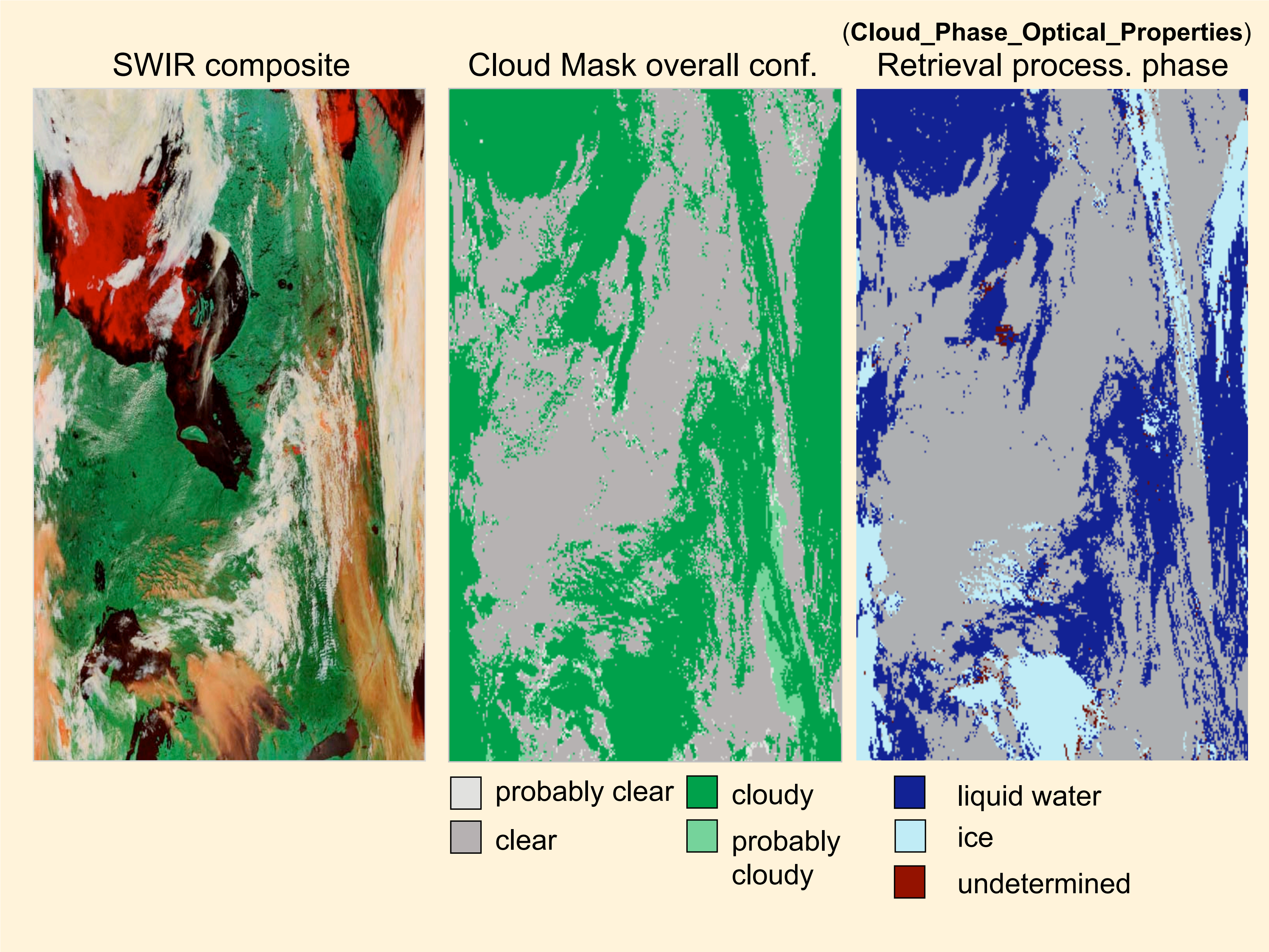


sea ice

ice cloud

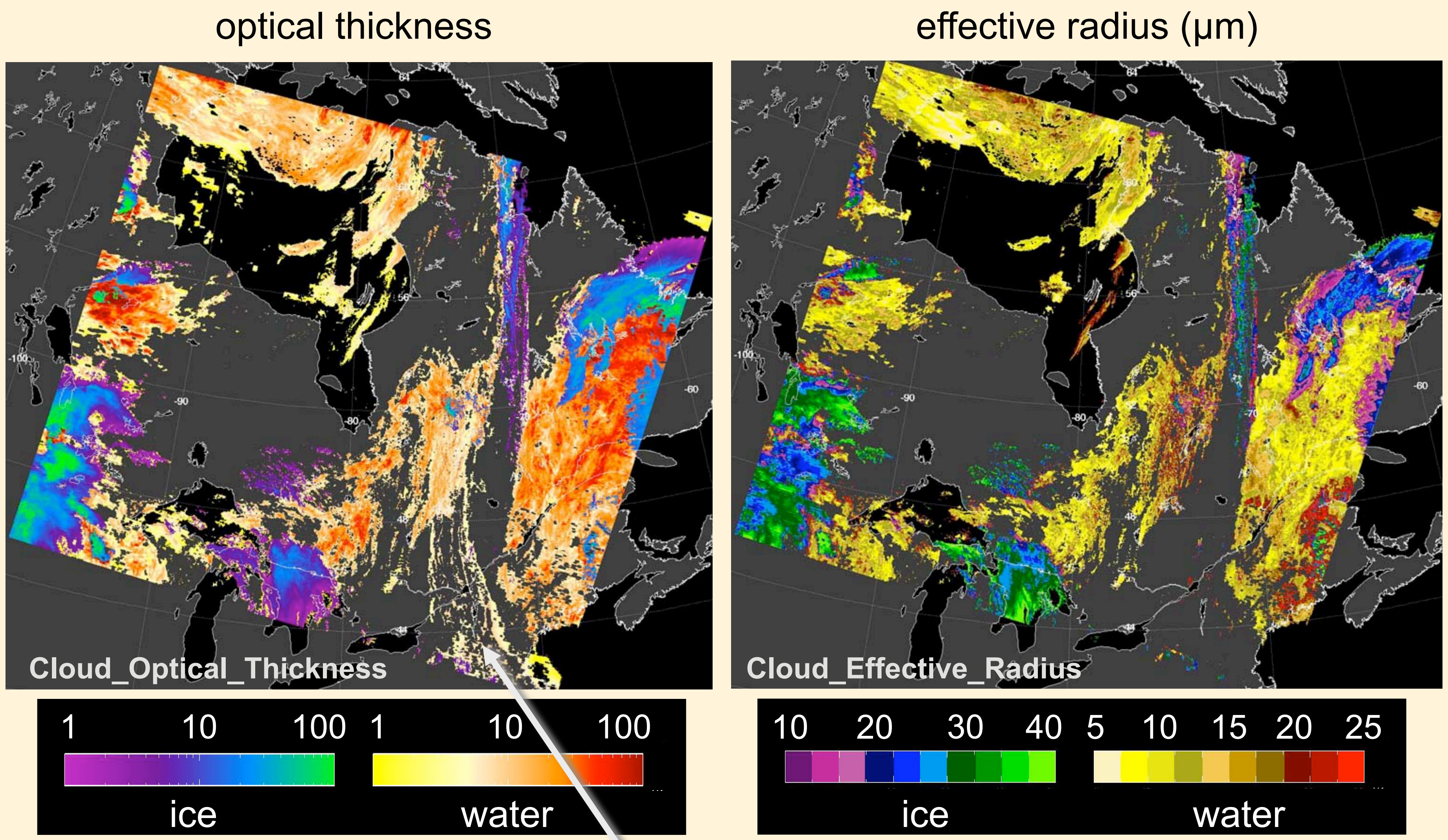
smoke


SWIR composite
Cloud Mask overall conf.
“Clear Sky Restoral”
probably clear
clear
cloudy
probably cloudy
spatial/spectral tests
edge detection
250m cloud mask



SWIR composite
Cloud Mask overall conf.
(Cloud_Phase_Optical_Properties)
Retrieval process. phase
probably clear
clear
cloudy
probably cloudy
liquid water
ice
undetermined

Optical Thickness, Effective Radius Retrievals

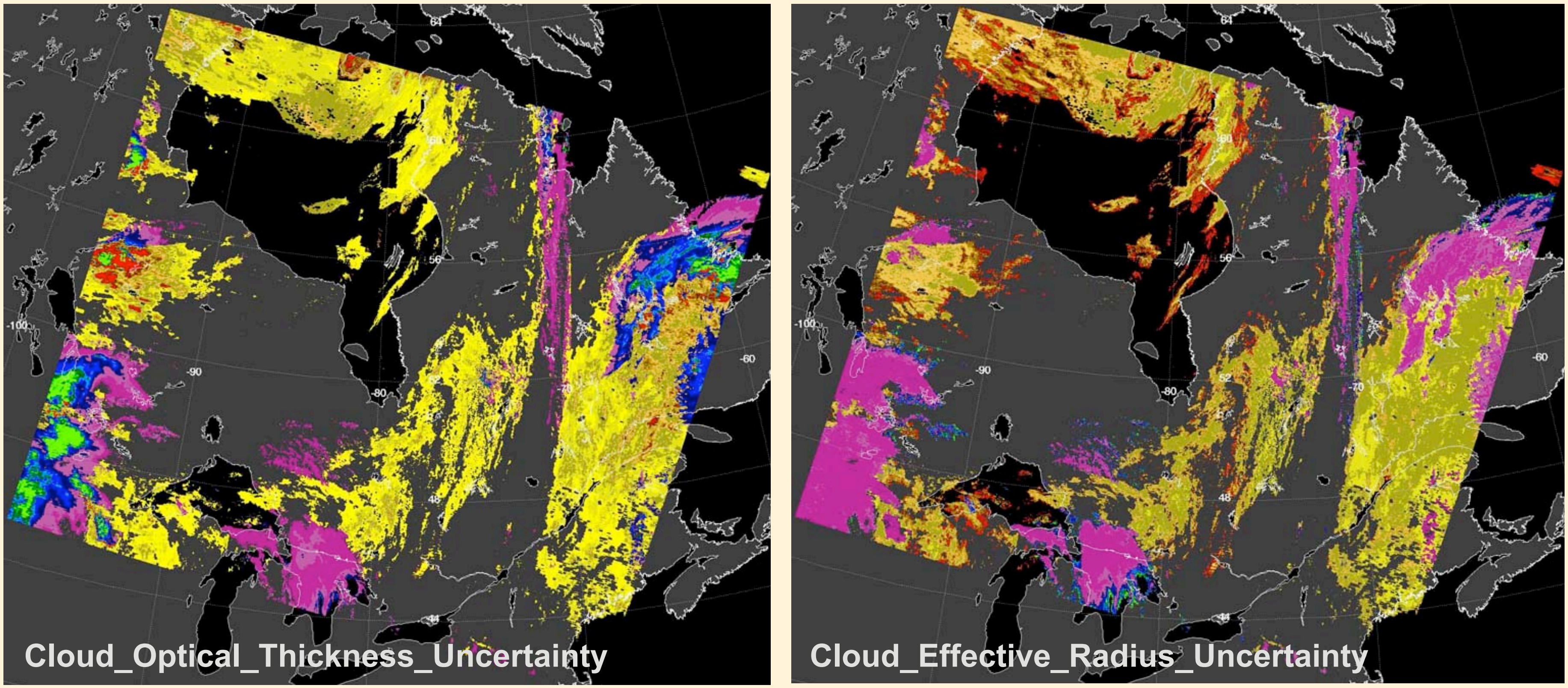


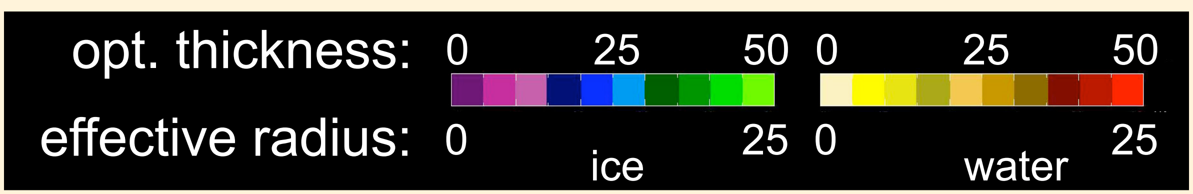
“partial” retrievals in C5 (not aggregated to L3)

Retrieval Uncertainty Estimates

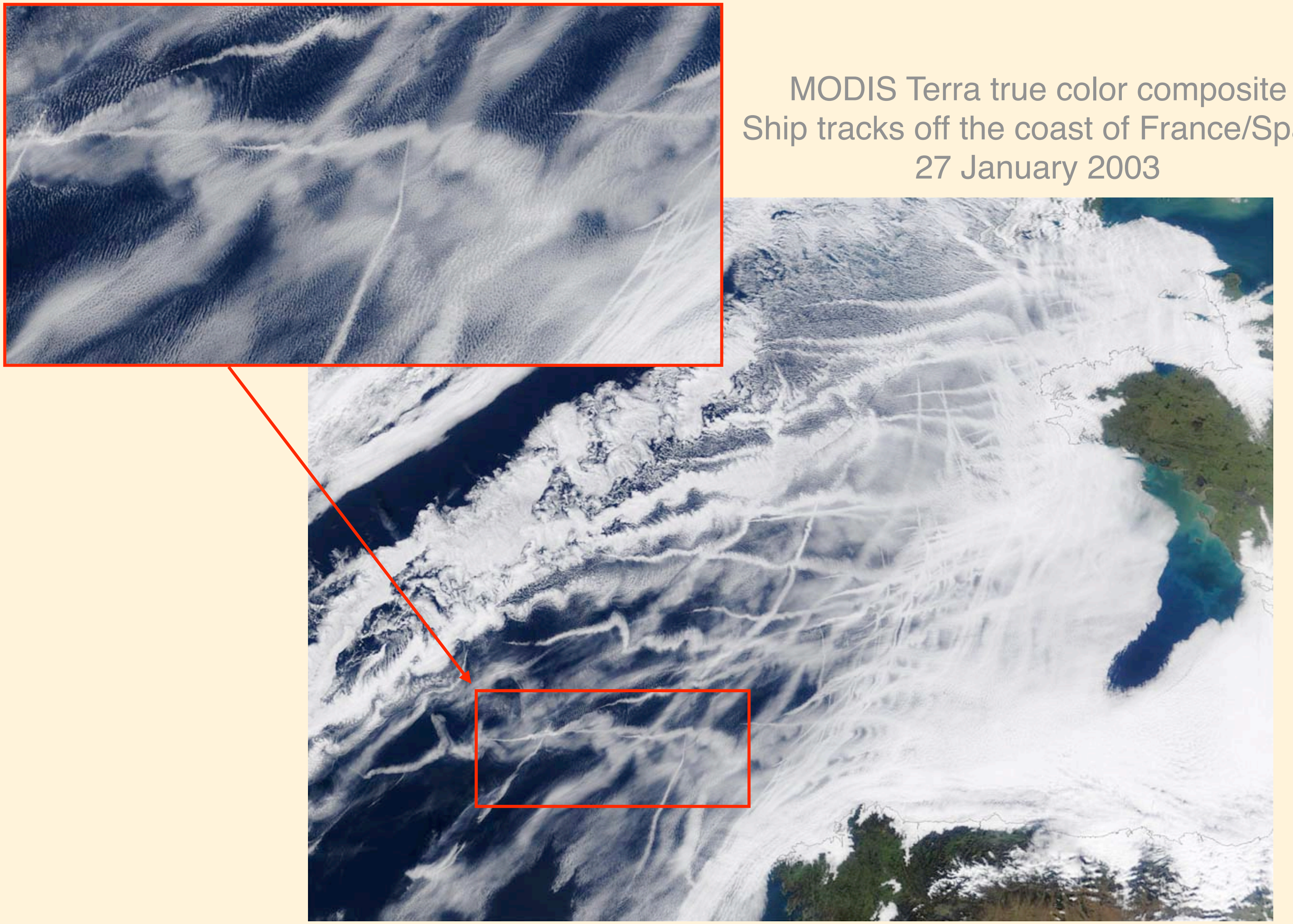
Error sources: cal./fwd. model (5%), sfc. albedo(15%), atmo. correction (20% PW_c)

$\Delta\tau_c / \tau_c$ (%) $\qquad\qquad$ $\Delta r_e / r_e$ (%)





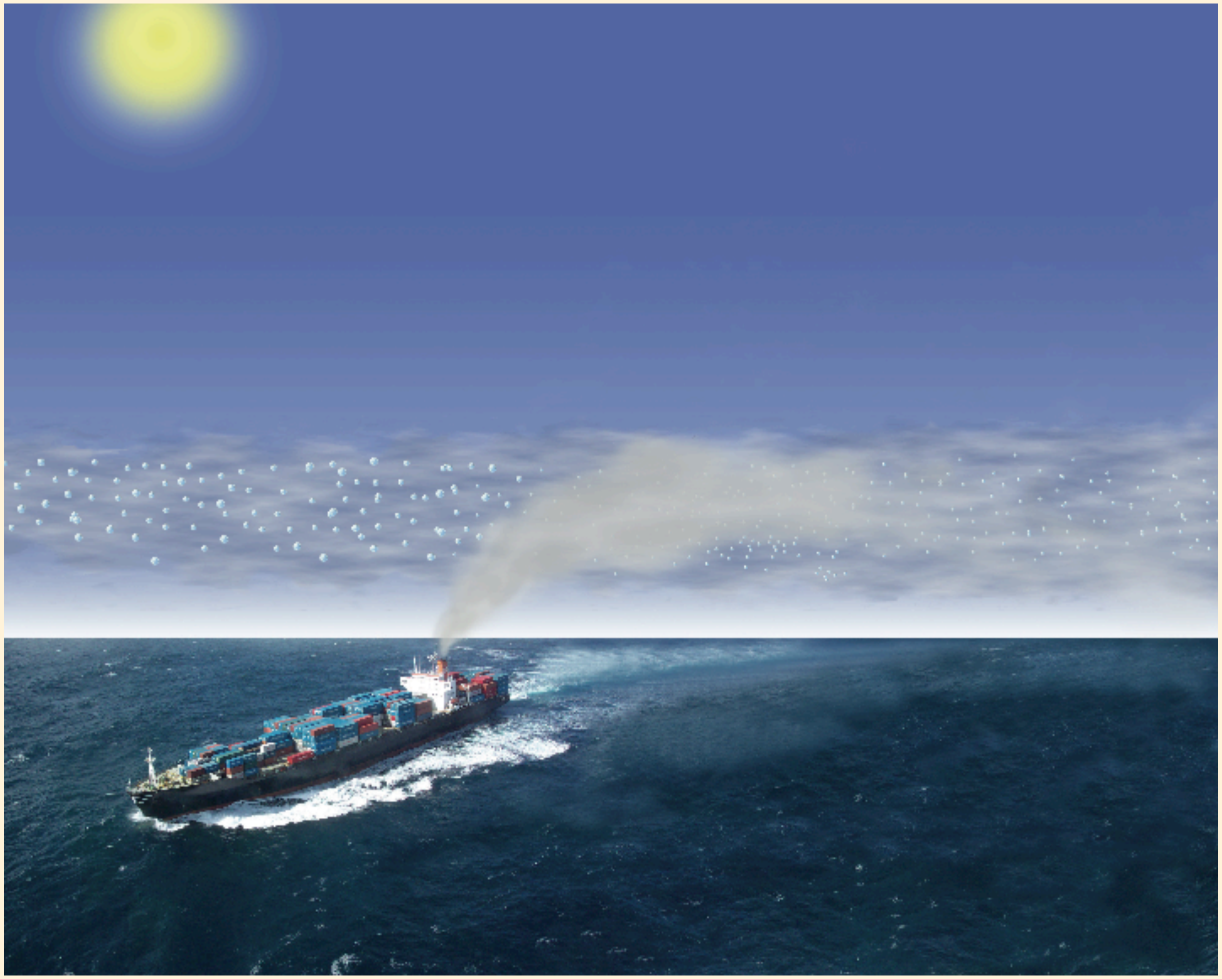
Ship Tracks: Ex. of Aerosol-Cloud Interactions



MODIS Terra true color composite
Ship tracks off the coast of France/Spain
27 January 2003

Aerosol-Cloud Interactions

Ship Track Schematic



RC-10 photograph, NASA ER-2 High Altitude Aircraft
MAST Experiment, June 2004

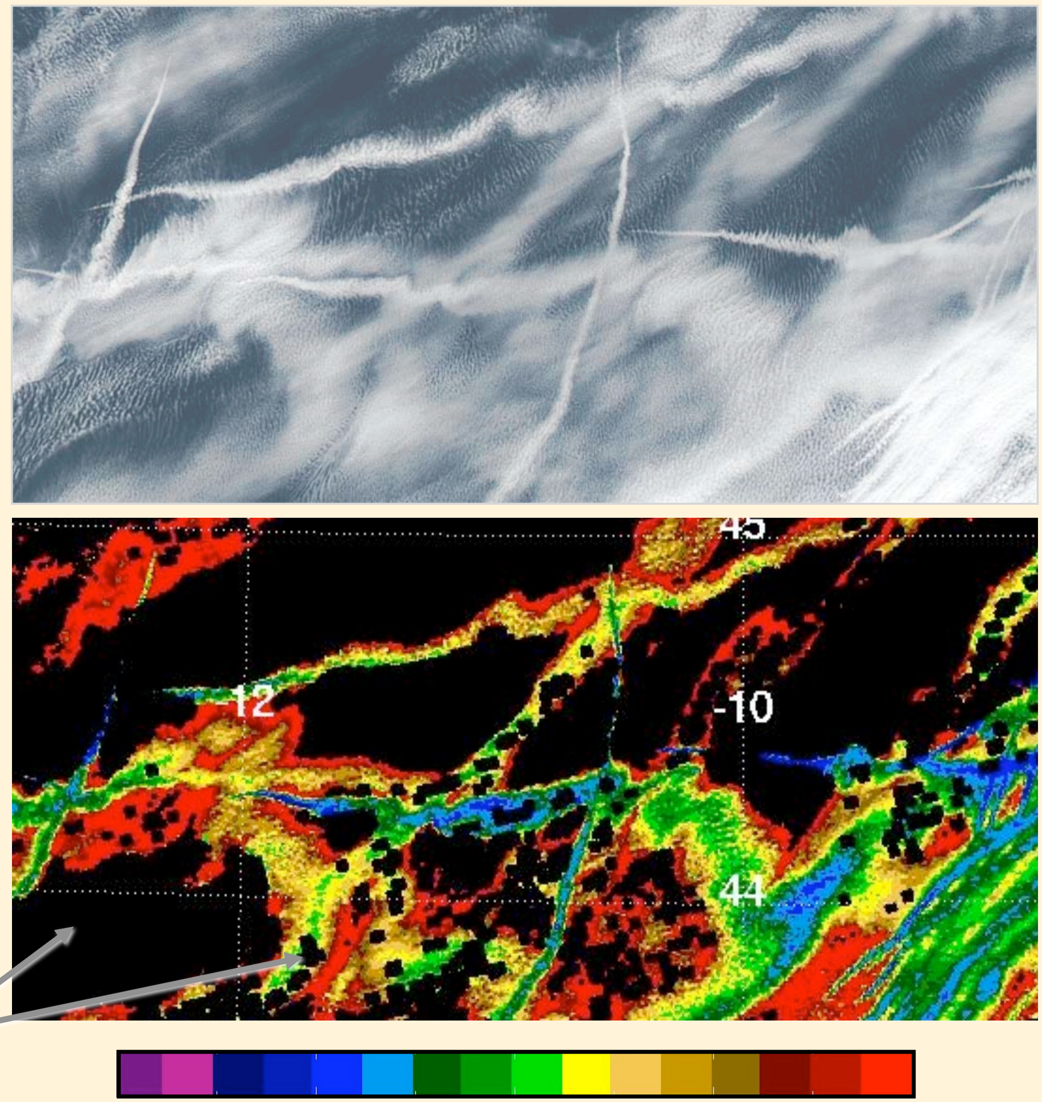
background cloud

ship track

unidentified container ship off Monterey Bay, CA, June 2004

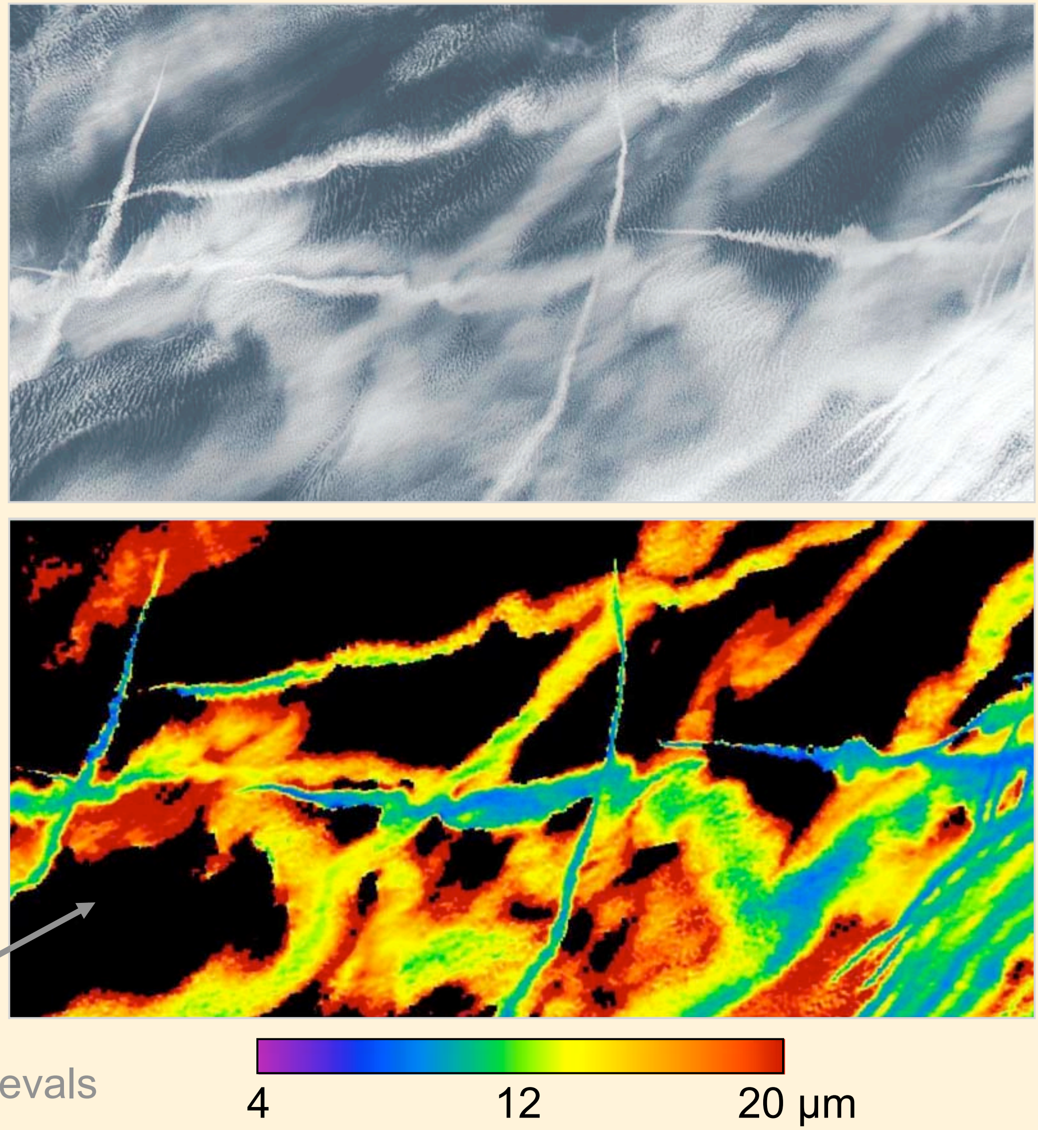
Aerosol-Cloud Interactions

MODIS Aqua retrievals, 27 January 2003



Aerosol-Cloud Interactions

MODIS Aqua retrievals, 27 January 2003



CSR off,
“failed” re retrievals

Water Path Retrieval Example

A Derived Quantity

<u>In general</u>:

$$R_\lambda = R\left(\tau_\lambda, \varpi_\lambda, g_\lambda\right)$$

For ice clouds, 3 optical variables can perhaps(?) be reduced to 1 optical and 2 microphysical:

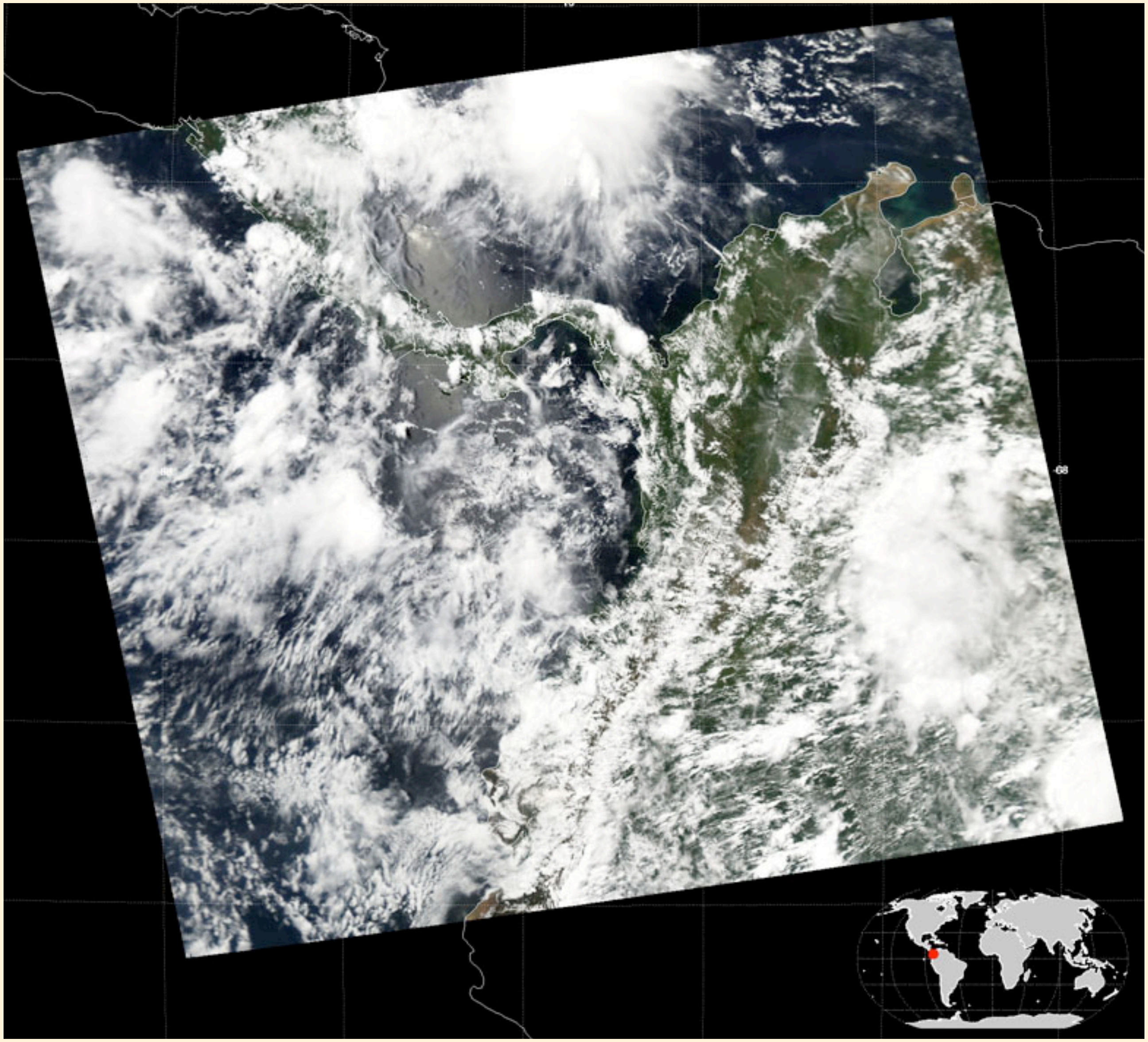
$$R_\lambda \approx R\left(\tau_{\lambda_0}, r_e, habit\ mixture\right)$$

$$\boxed{\text{if } r_e \equiv \frac{3}{4}\frac{\langle V \rangle}{\langle A_{cs} \rangle} \Rightarrow IWP = \frac{4\rho_i}{3Q_e\left(\lambda_0, r_e\right)} \tau_{\lambda_0} r_e}$$

Assumption: vertically homogenous cloud layer, i.e., $N, r_e \neq f(z)$

MODIS Aqua Example

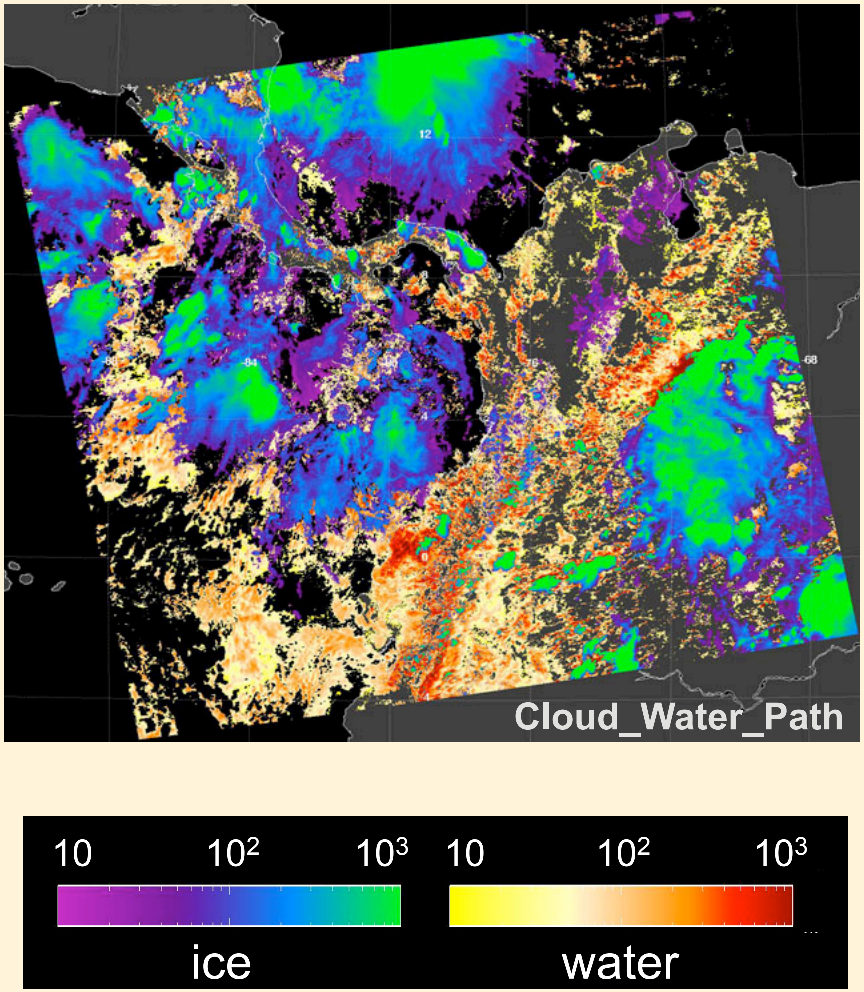
20 Aug 2006, Central Am./NW SA, true color composite



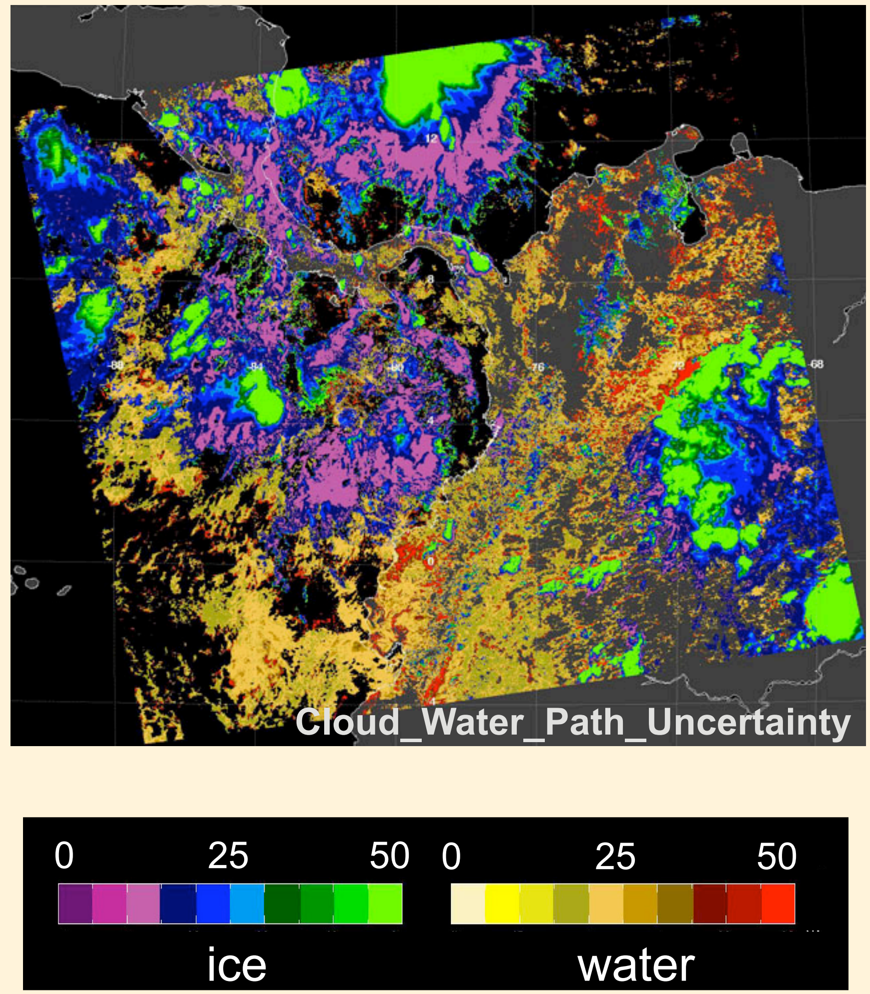
MODIS Aqua Example, cont.

IWP, LWP, and Baseline Uncertainty Estimate

WP (gm^{-2})



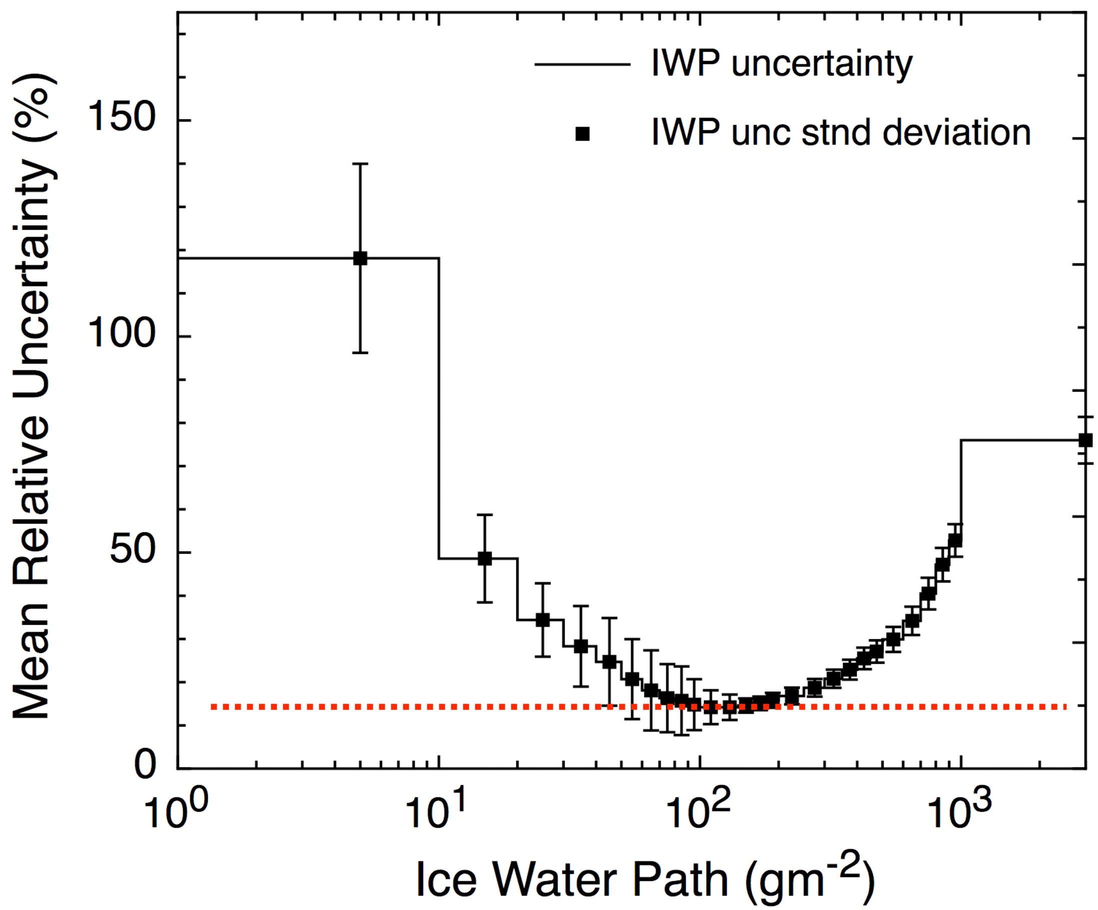
$\Delta WP/WP$ (%)



Error sources: calibration/forward model,
surface albedo, atmospheric correction

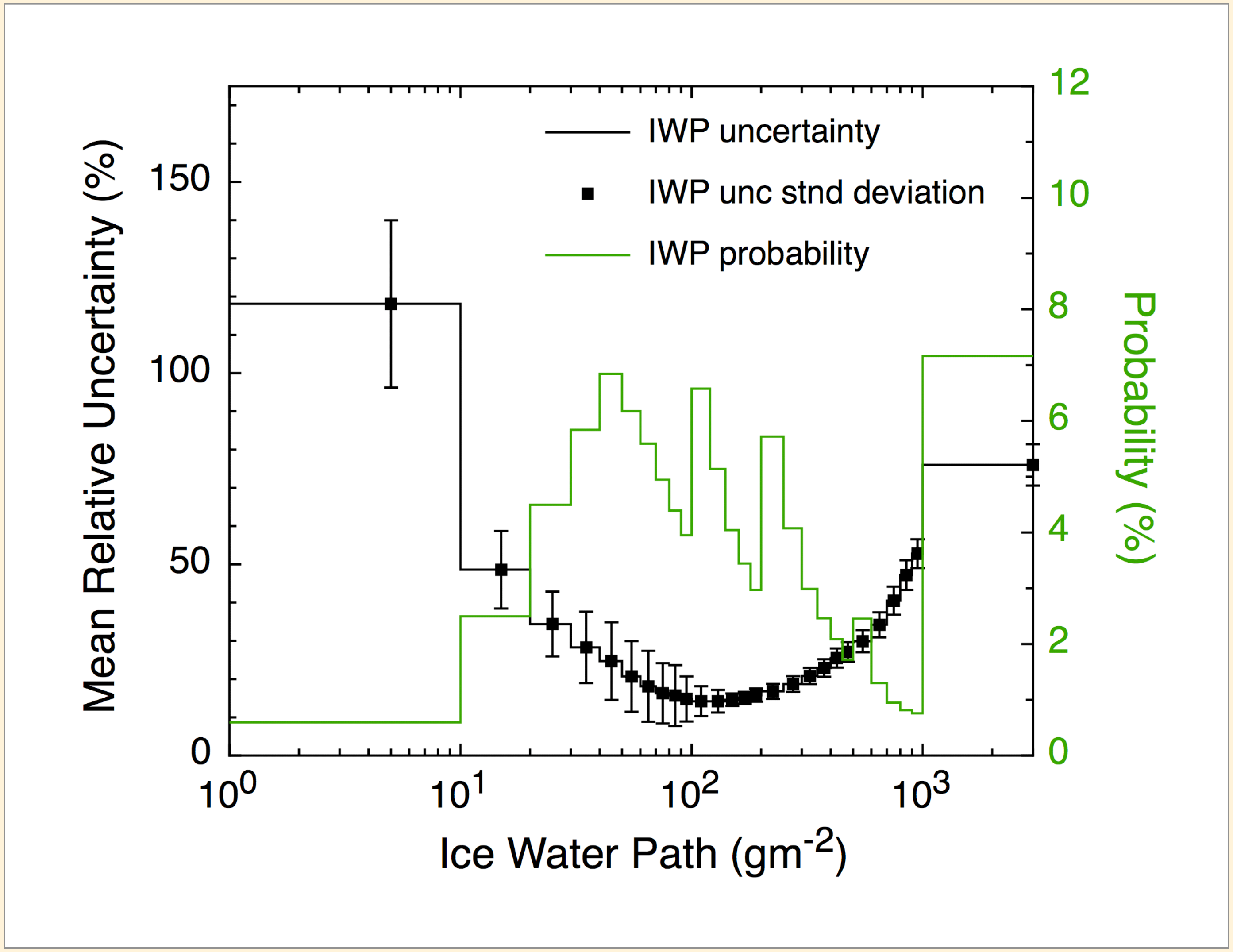
MODIS Aqua Example, cont.

Uncertainty vs. IWP: Ocean Pixels Only



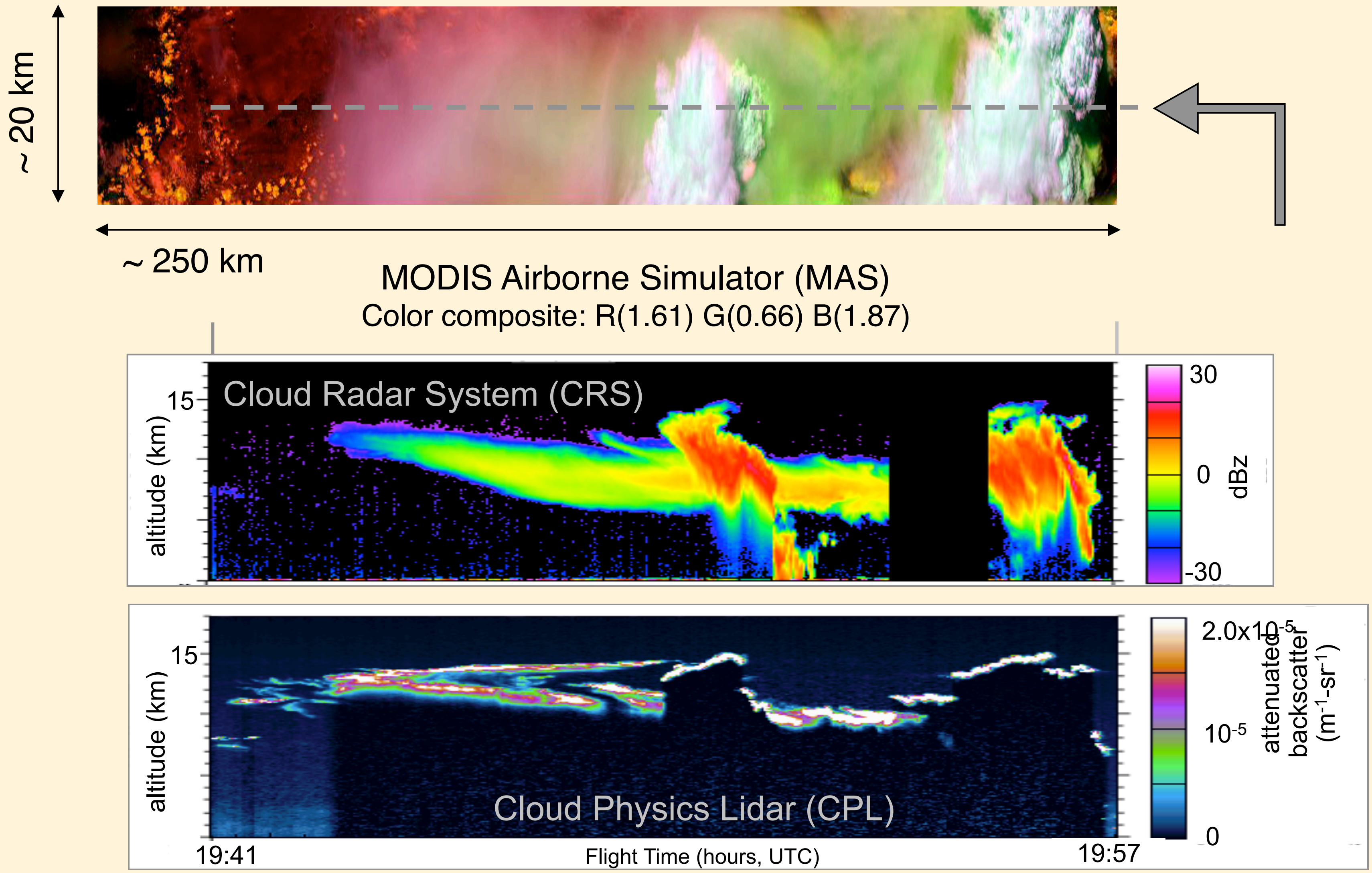
MODIS Aqua Example, cont.

Uncertainty vs. IWP: Ocean Pixels Only



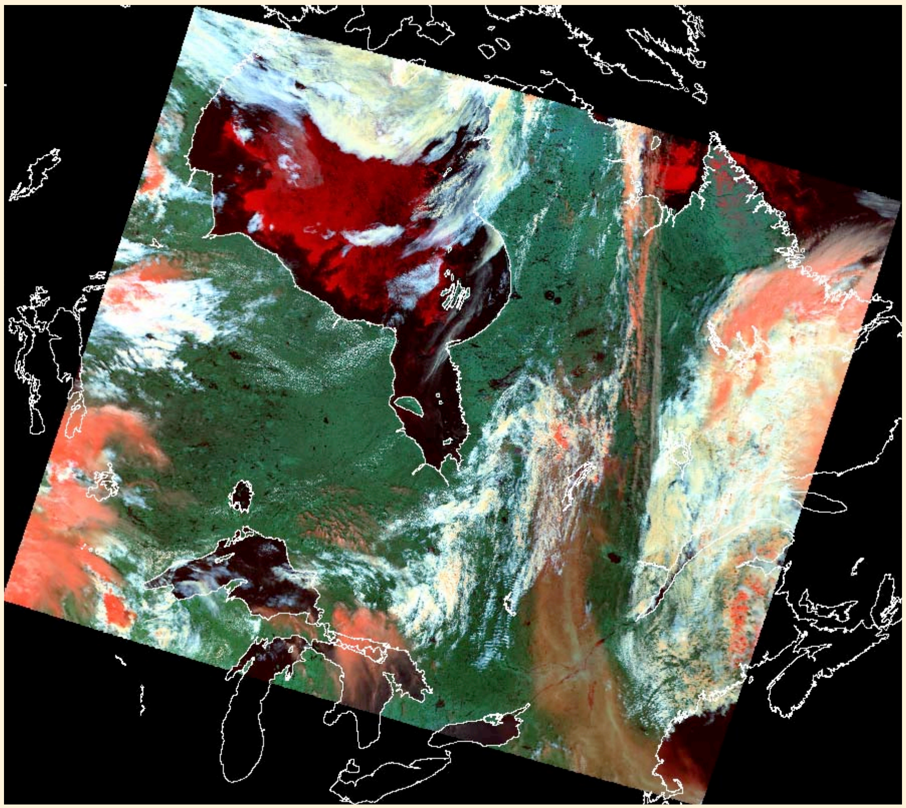
Issues with Multilayer Clouds

- Observations: CRYSTAL-FACE (23 July, Track 8)

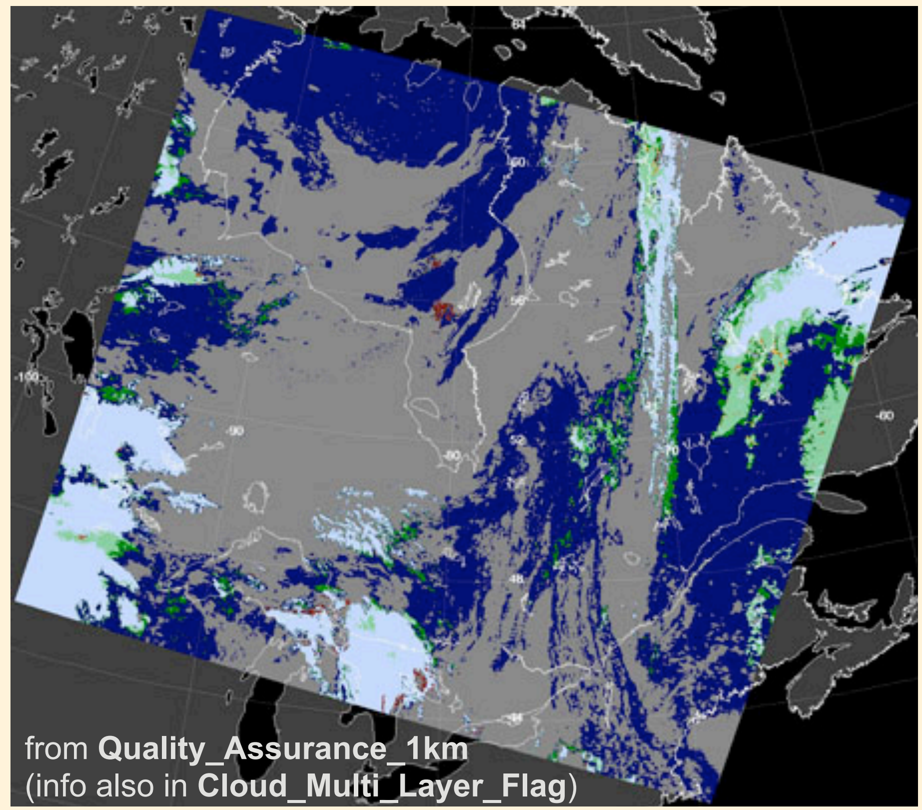


Multilayer Flag - A Research Product

- Multilayers of different phases: disagreement between IR-phase retrieval and phase derived for optical/microphysical retrieval (SWIR bands, cloud mask tests, …).
- General multilayer: 0.94 μm water vapor absorption band.



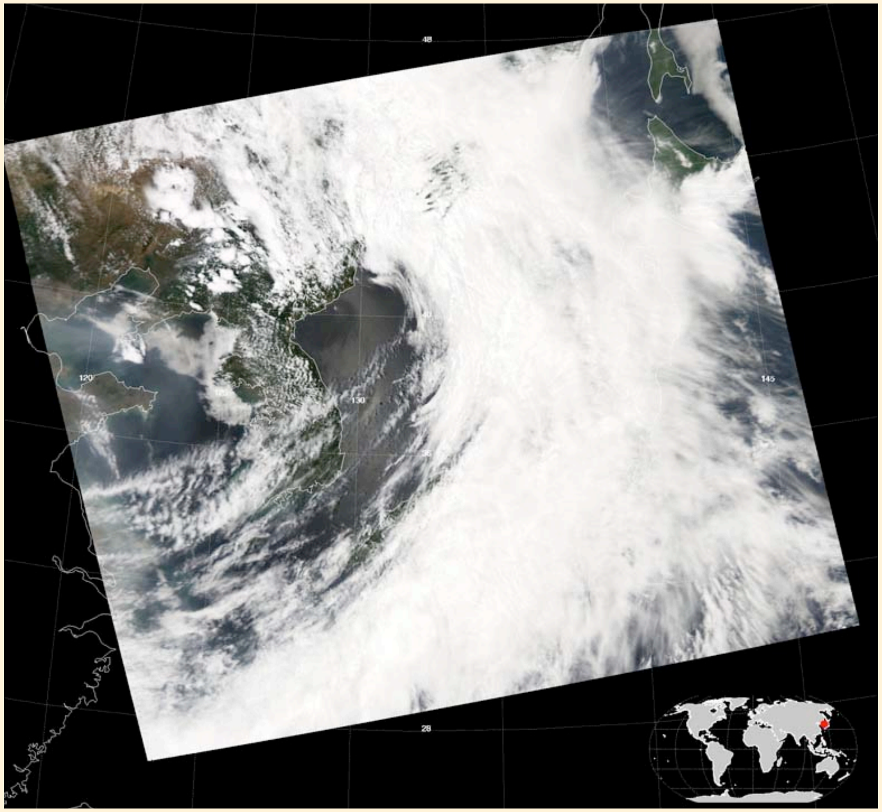
SWIR composite



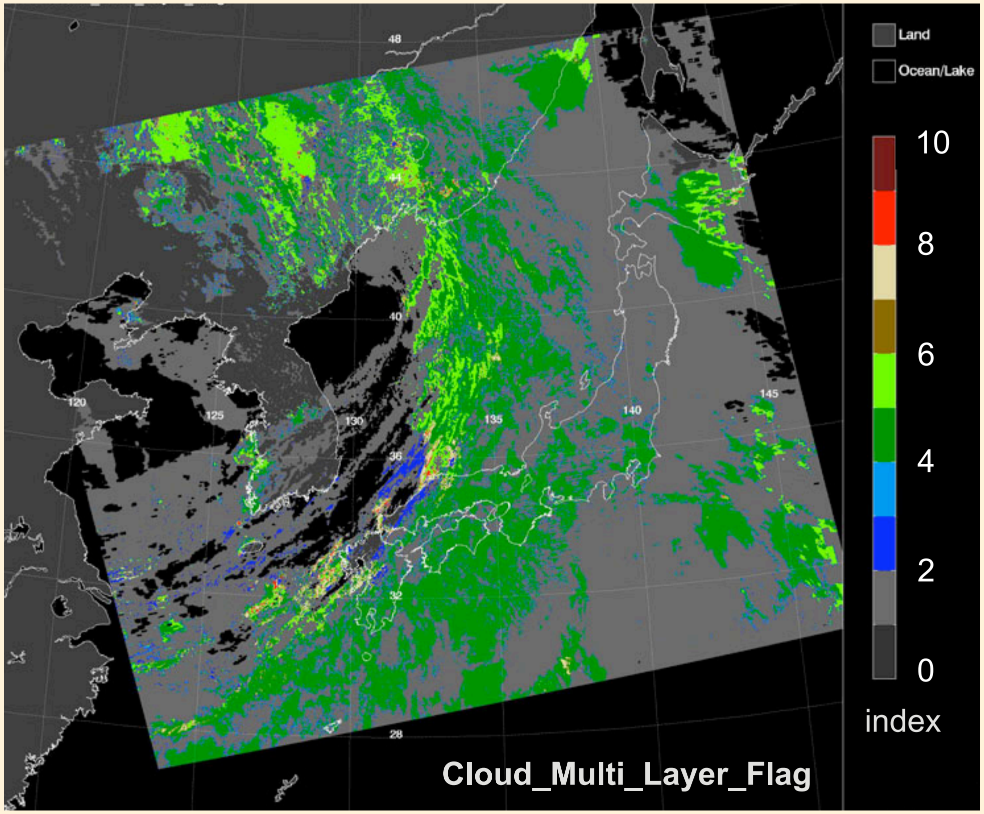
liquid water
ice
undetermined
ML, retr'd as water
ML, retr'd as ice
ML undetermined

Multilayer Flag, cont.

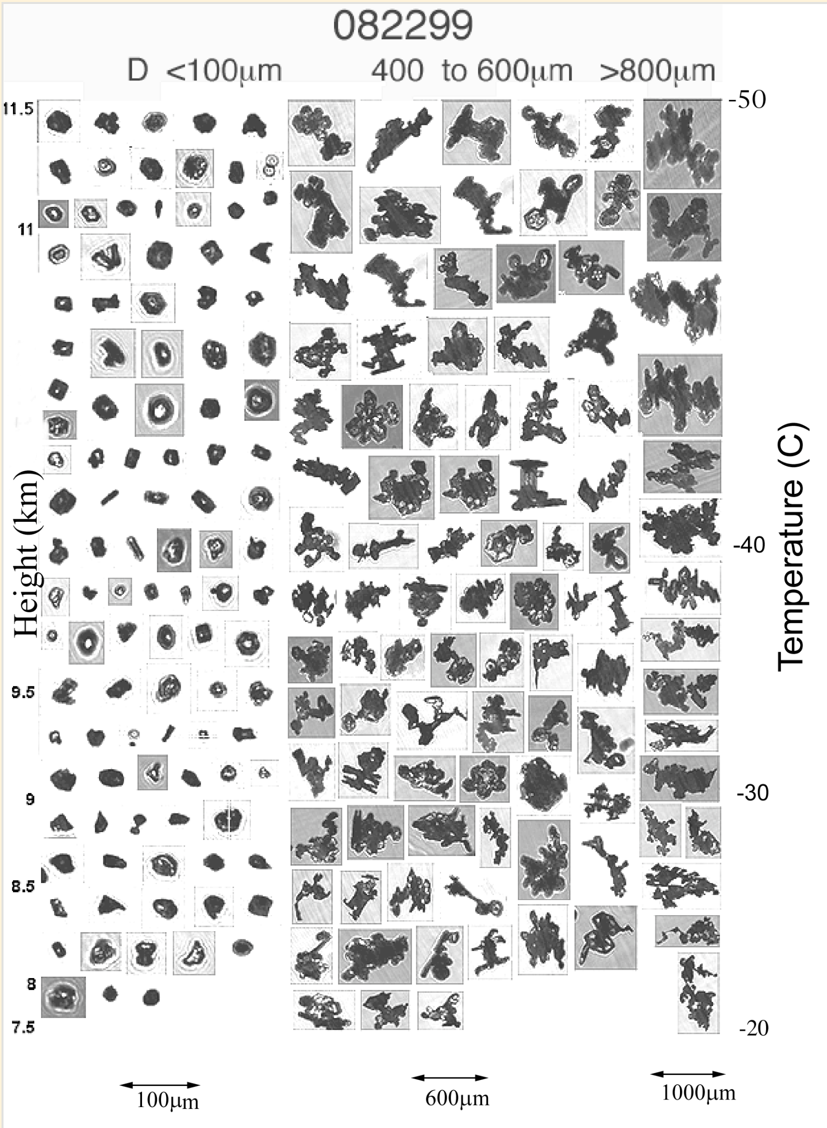
MODIS Aqua, 15 June 2006, 0415 UTC

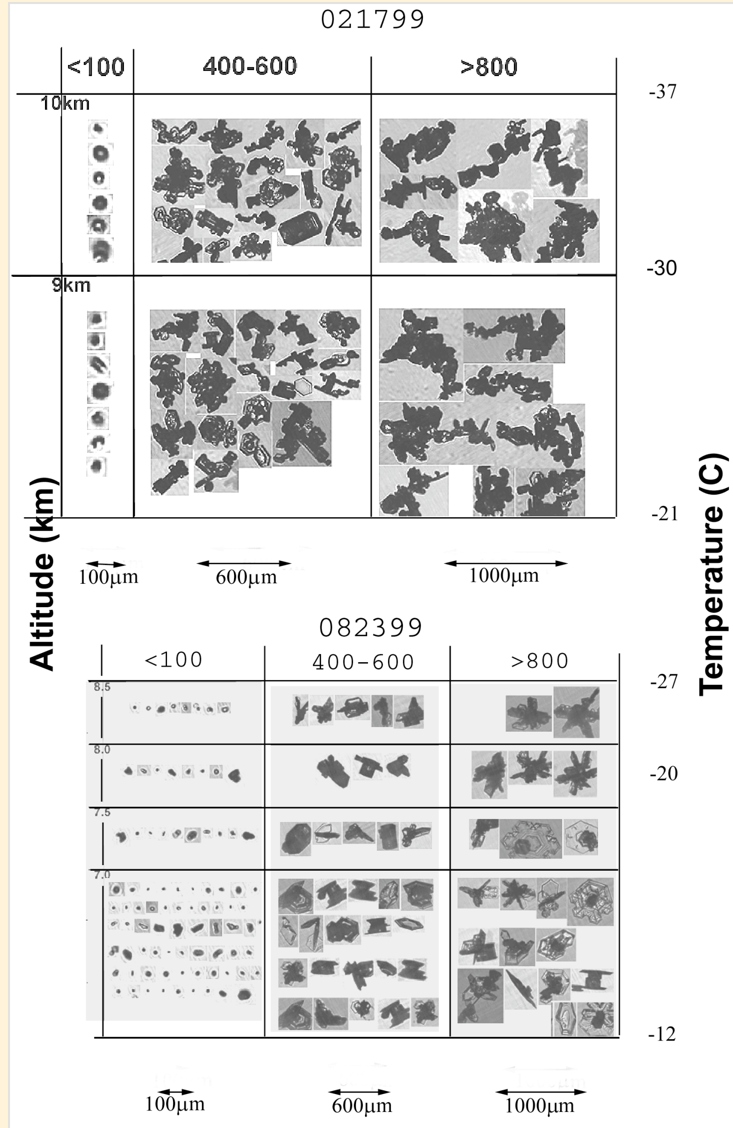


RGB composite



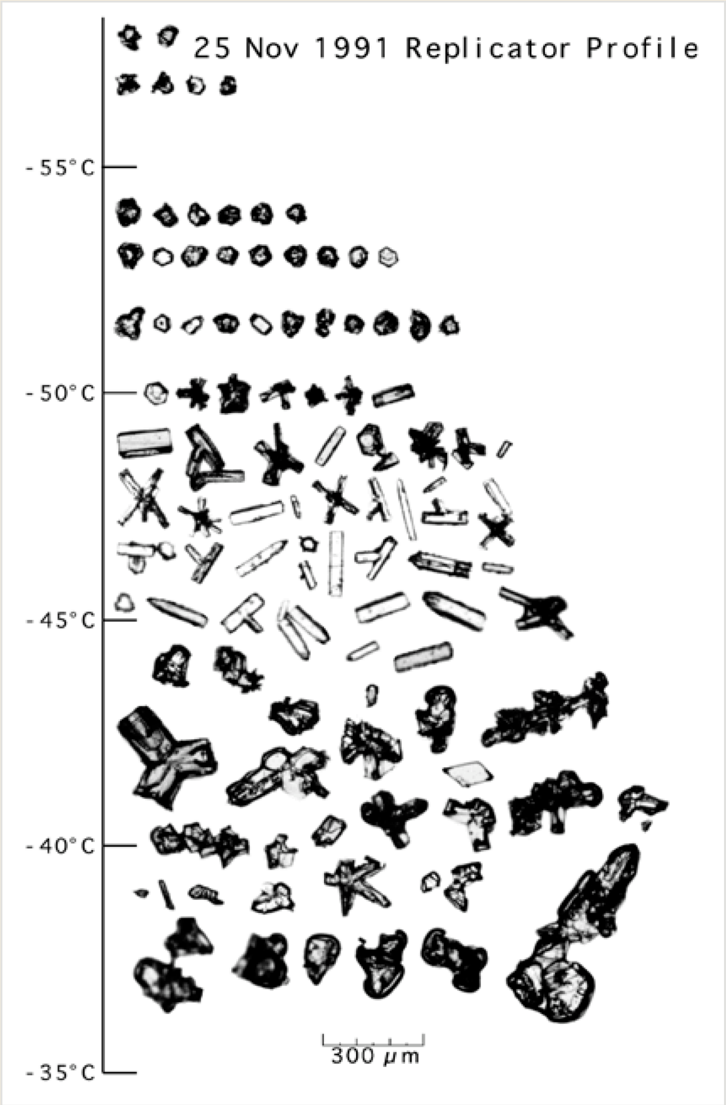
Ice Particle Profiles from Tropical Cirrus Anvils

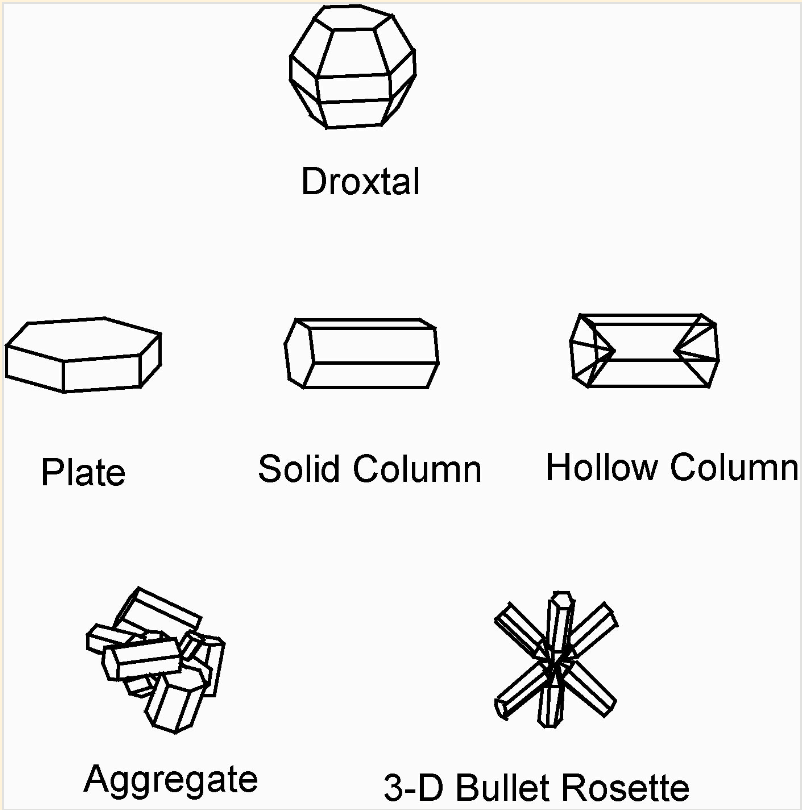




Replicator Particle Habits

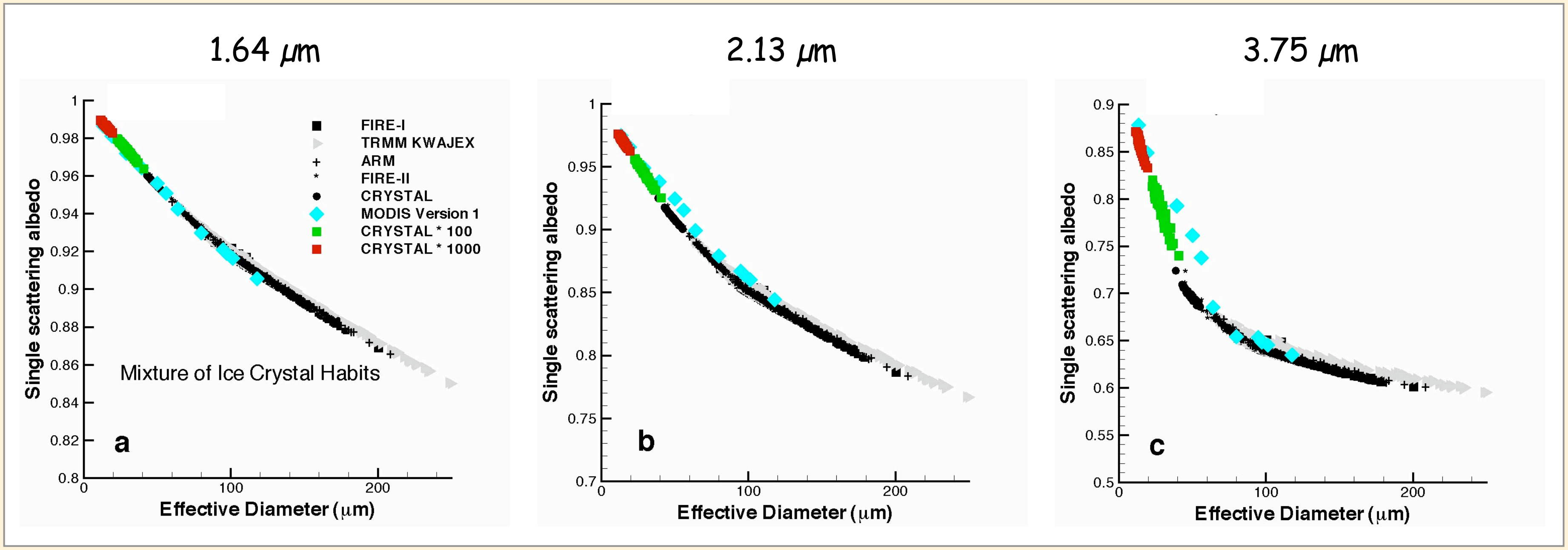
Simulated Particle Habits





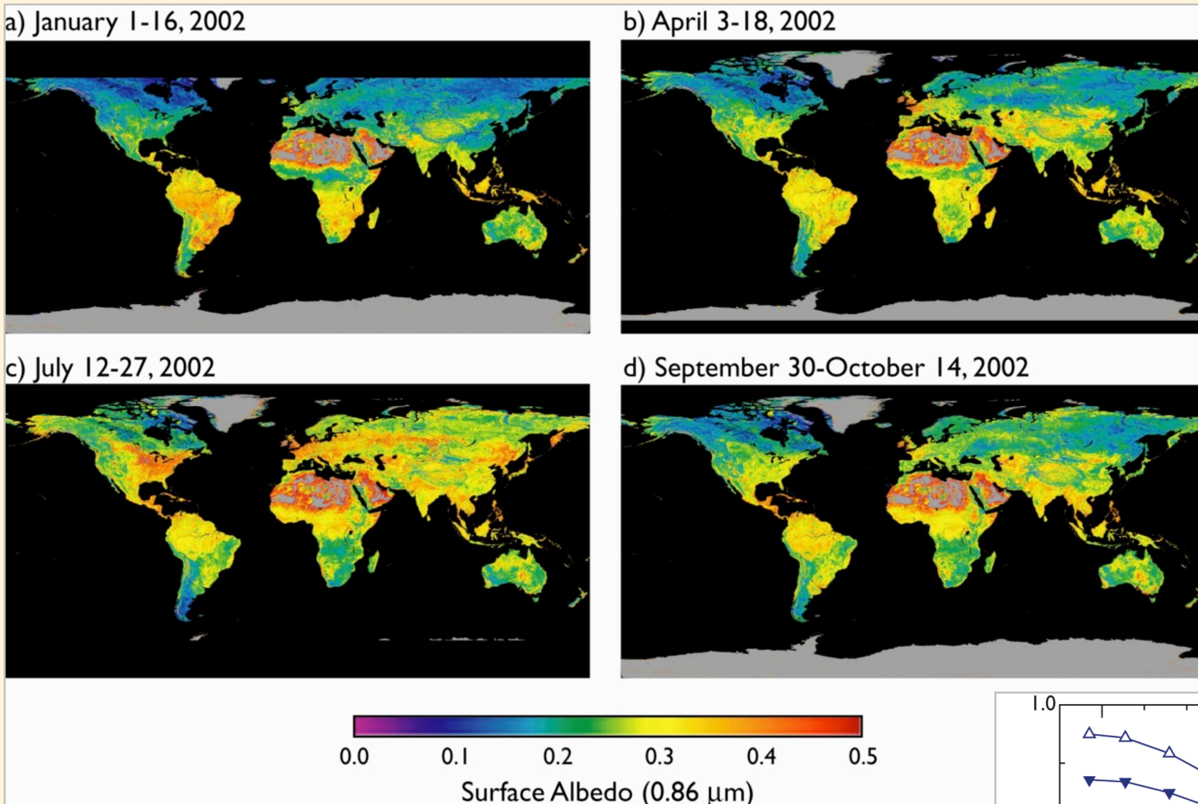
MODIS Collection 5 Ice Model Single Scattering Albedo

(from *Baum et al.*, JAS, 2005)

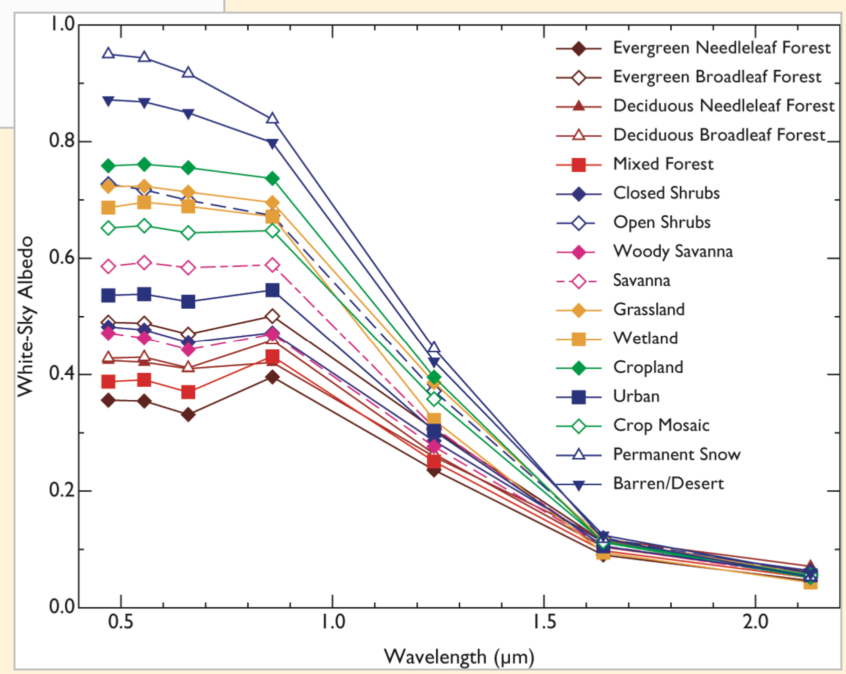


Can replicate the MODIS Version 1 properties by arbitrarily increasing the number of small particles for a set of particle size distributions (from a CRYSTAL case of very high level cirrus near the tropopause)

Spectral Surface Albedo Examples



Spatially complete “white-sky” albedo in the MODIS 0.86 μm band for four 16-day periods in 2002 (*after Moody et al. 2005a*).



Northern hemisphere multi-year average white-sky spectral snow albedo as a function of selected IGBP ecosystem classifications from 2000-2004 MOD43B3 data (*after Moody et al. 2006b*).

Gridded Level-3 Joint Atmosphere Products

(M. D. King, S. Platnick, P. A. Hubanks – NASA GSFC)

- Daily, 8-day, and monthly products (97, 255, 255 MB)
  - 20-25% of the size of these products in Collection 4
  - Files contain more SDSs, but are stored with internal hdf compression
- 1° ×1° equal angle grid
- Statistics
  - Mean, standard deviation, minimum, maximum
  - QA mean, QA standard deviation
  - Cloud fraction, pixel counts
  - Log mean, log standard deviation (useful for cloud inhomogeneity studies)
  - Mean uncertainty, QA mean uncertainty
  - Marginal probability density functions for cloud properties
    - Histogram counts, confidence histograms
  - Joint probability density functions
    - Joint histograms between various cloud properties (e.g., cloud optical thickness vs. cloud-top pressure)

MODIS Atmosphere Team Daily Global (08_D3) Statistics

ex. table for "primary retrieval" Cloud Optical Properties (MOD/MYD06_L2)

Collection 5 Updates

- Added
- Renamed
- Deleted

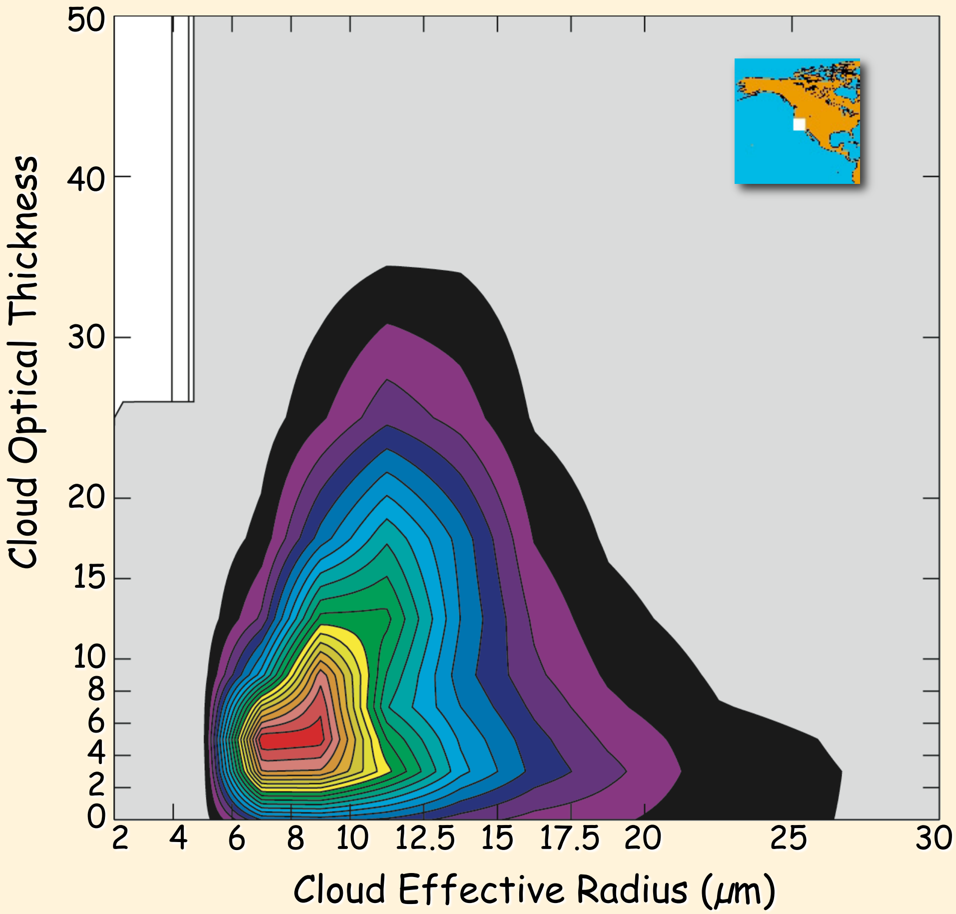
Parameter	Mean	Standard_Deviation	Minimum	Maximum	QA_Mean	QA_Standard_Deviation	Histogram_Counts (n)	Confidence_Histogram (4)	Fraction	Pixel_Counts	Mean_Uncertainty	QA_Mean_Uncertainty	Log_Mean_Uncertainty	QA_Log_Mean_Uncertainty	Log_Mean	Log_Standard_Deviation	QA_Log_Mean	QA_Log_Standard_Deviation	Regression_Slope	Regression_Intercept	Regression_R-Squared	Regression_Mean_Square_Error	Joint_Histogram_vs_Effect_Radius (nxn)	Joint_Histogram_vs_Temperature (nxn)	Joint_Histogram_vs_Emissivity (nxn)	Joint_Histogram_vs_Pressure (nxn)
Derived from L2 Cloud (06_L2)																										
Cloud Optical Properties (Primary Retrieval)																										
58. Cloud_Optical_Thickness_Liquid	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•					•	•	•	•
59. Cloud_Optical_Thickness_Ice	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•					•	•	•	•
60. Cloud_Optical_Thickness_Undetermined	•	•	•	•	•	•									•	•	•	•								
61. Cloud_Optical_Thickness_Combined	•	•	•	•	•	•									•	•	•	•								
62. Cloud_Optical_Thickness_ISCCP[8]																										•
63. Cloud_Effective_Radius_Liquid	•	•	•	•	•	•	•	•			•	•												•	•	•
64. Cloud_Effective_Radius_Ice	•	•	•	•	•	•	•	•			•	•												•	•	•
65. Cloud_Effective_Radius_Undetermined	•	•	•	•	•	•																				
66. Cloud_Effective_Radius_Combined	•	•	•	•	•	•																				
67. Cloud_Water_Path_Liquid	•	•	•	•	•	•	•	•			•	•														
68. Cloud_Water_Path_Ice	•	•	•	•	•	•	•	•			•	•														
69. Cloud_Water_Path_Undetermined	•	•	•	•	•	•																				
70. Cloud_Water_Path_Combined	•	•	•	•	•	•																				
71. Cloud_Phase_Optical_Properties																								•		
(Primary Cloud Fraction)																										
72. Cloud_Fraction_Liquid									•	•																
73. Cloud_Fraction_Ice									•	•																
74. Cloud_Fraction_Undetermined									•	•																
75. Cloud_Fraction_Combined									•	•																

Full details at modis-atmos.gsfc.nasa.gov

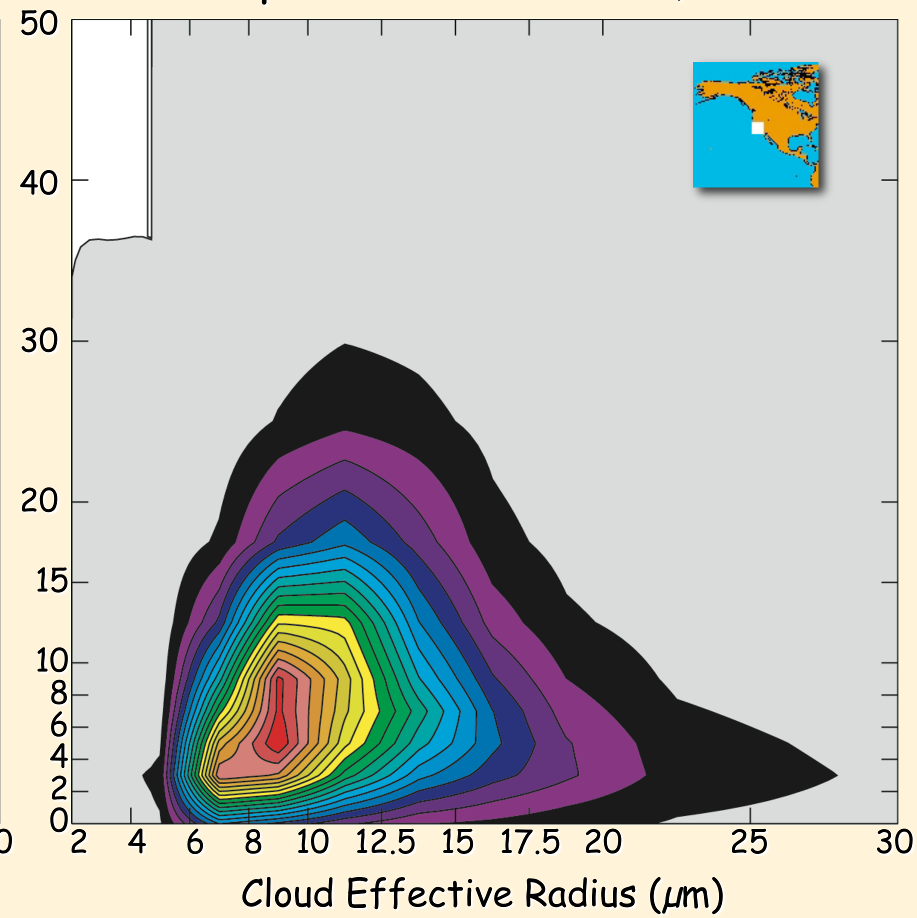
California / California Current Regime
Monthly Joint Histogram Counts of Liquid Water Clouds over Ocean

32°-40°N, 117°-125°W
June 2003

Terra/MODIS (AM Overpass)

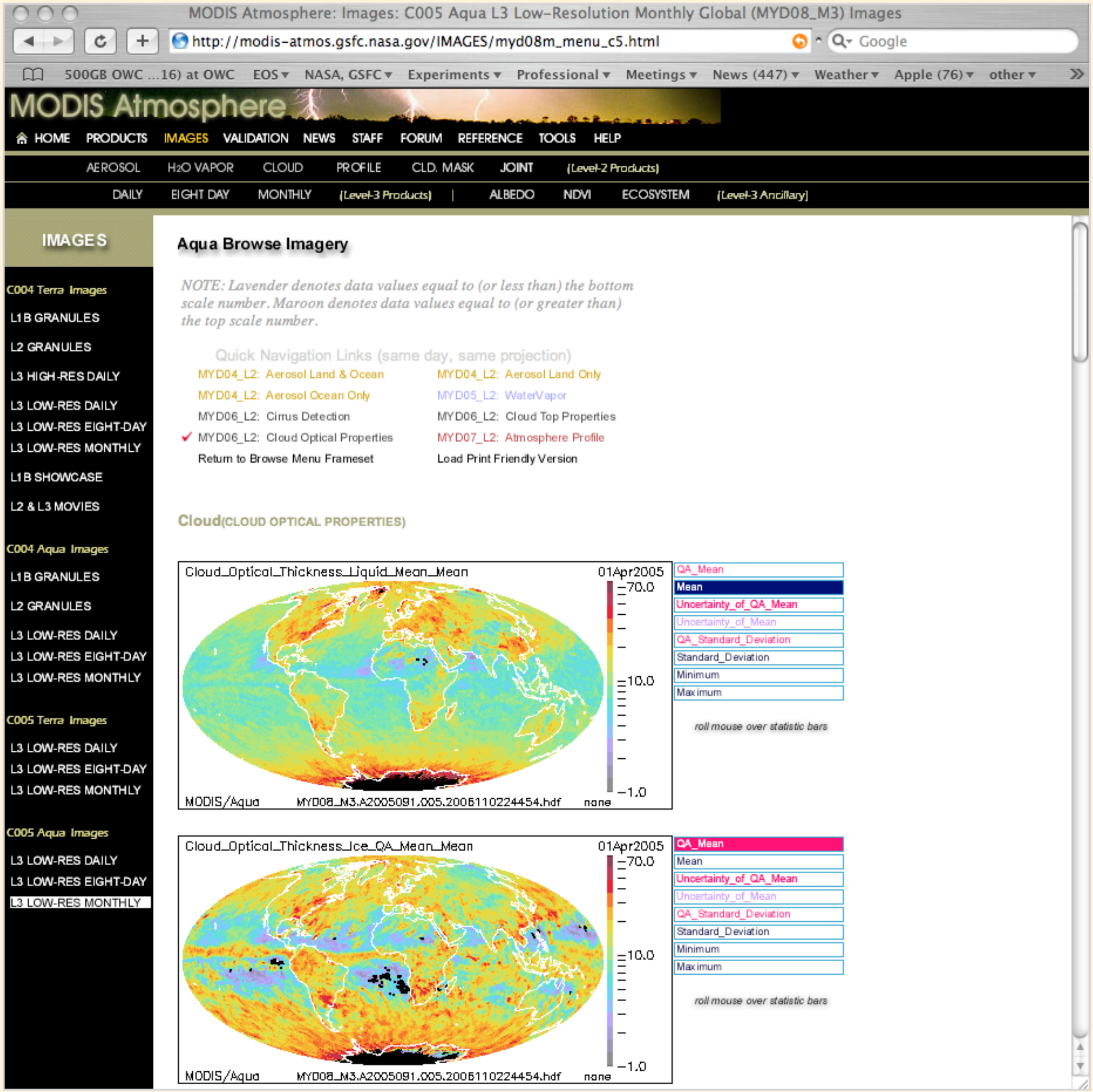


Aqua/MODIS (PM Overpass)



MODIS Level-3 Daily Global Browse Images

modis-atmos.gsfc.nasa.gov



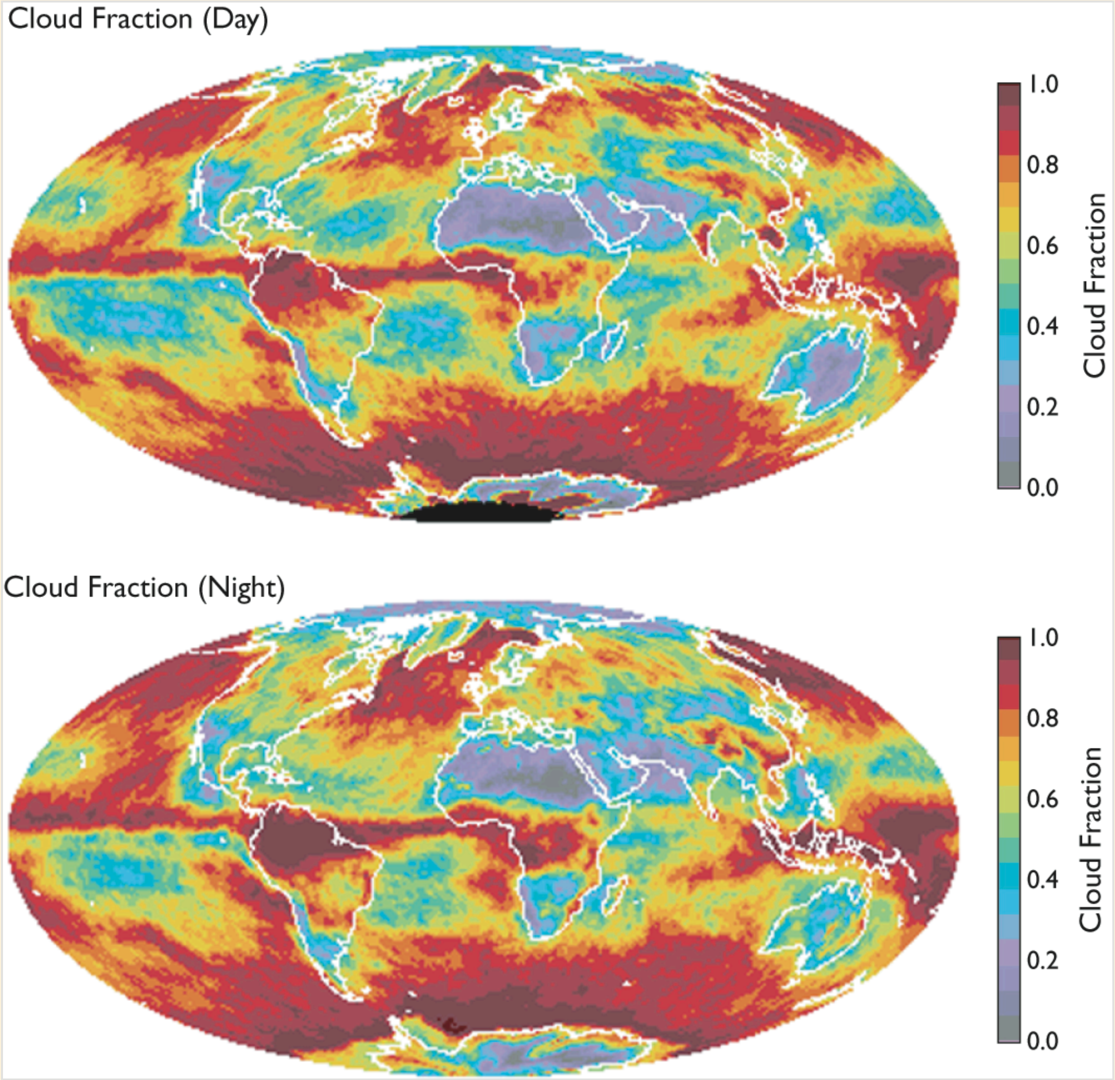
Monthly Mean Cloud Fraction (Cloud Mask)

(S. A. Ackerman, R. A. Frey et al. – Univ. Wisconsin)

April 2005
Aqua C5

Cloud_Fraction_Day_Mean_Mean

Cloud_Fraction_Night_Mean_Mean



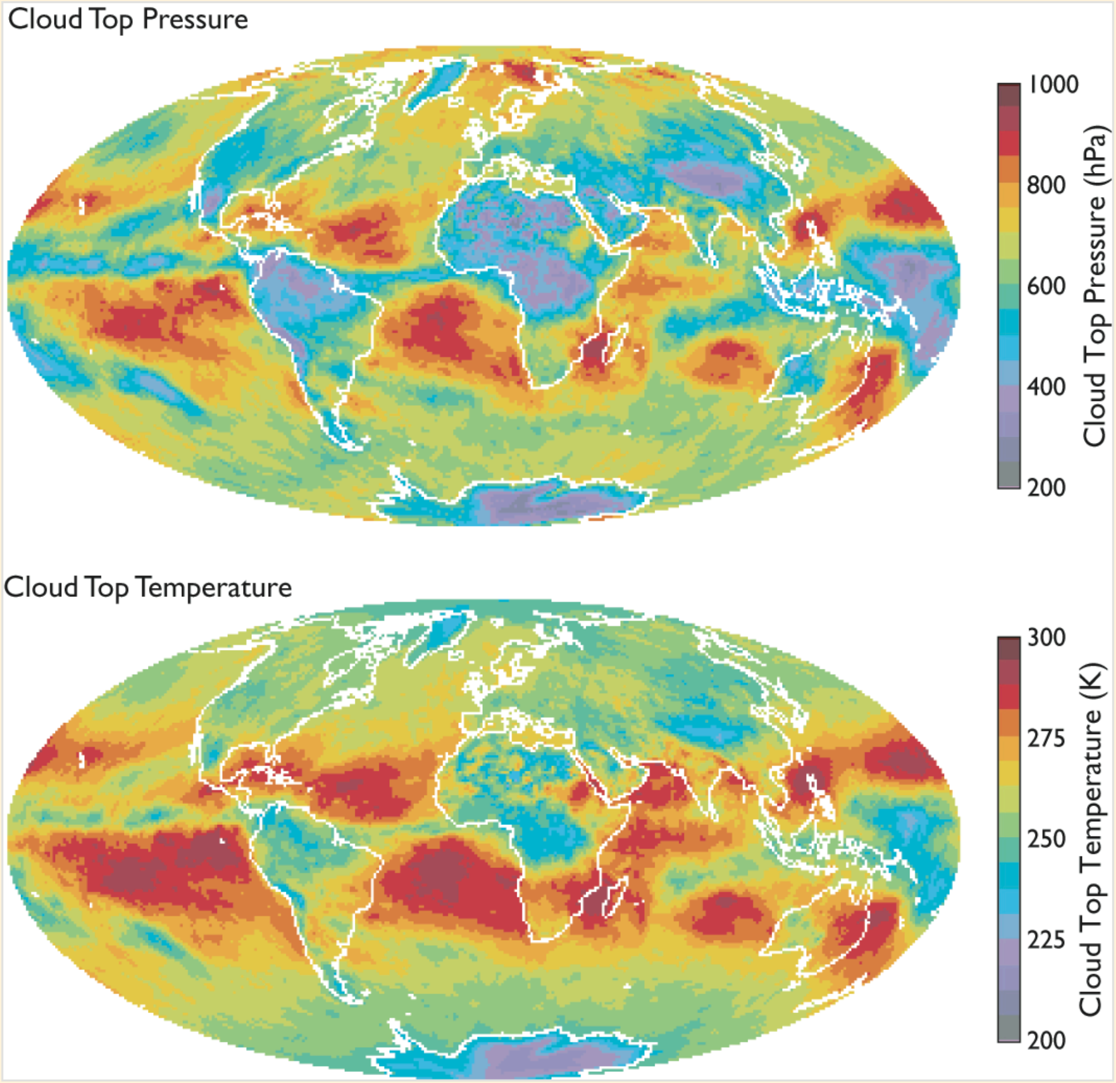
Monthly Mean Cloud-Top Properties

(W. P. Menzel, R. A. Frey et al. – Univ. Wisconsin)

April 2005
Aqua C5

Cloud_Top_Pressure_Mean_Mean

Cloud_Top_Temperature_Mean_Mean

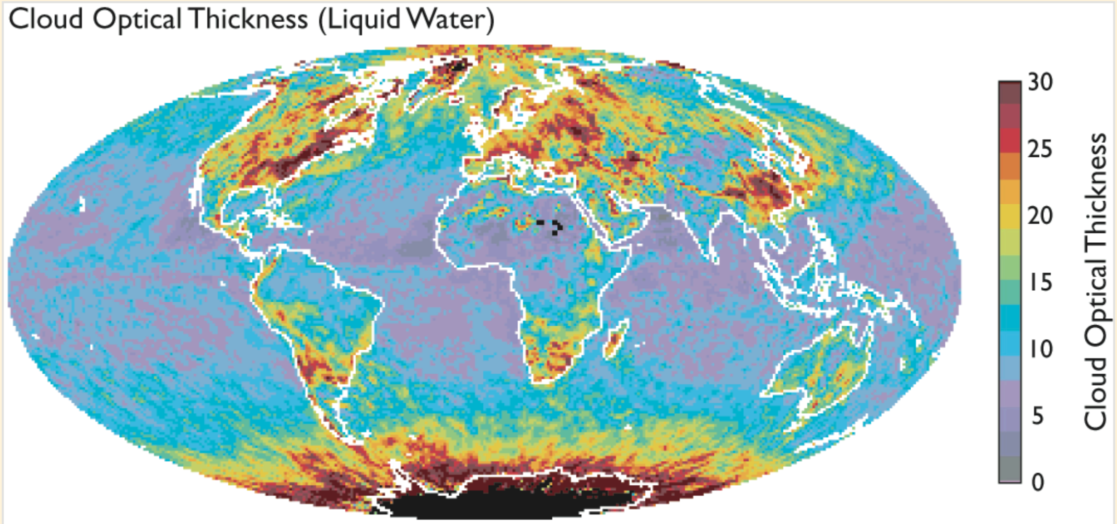


Monthly Mean Cloud Optical Thickness

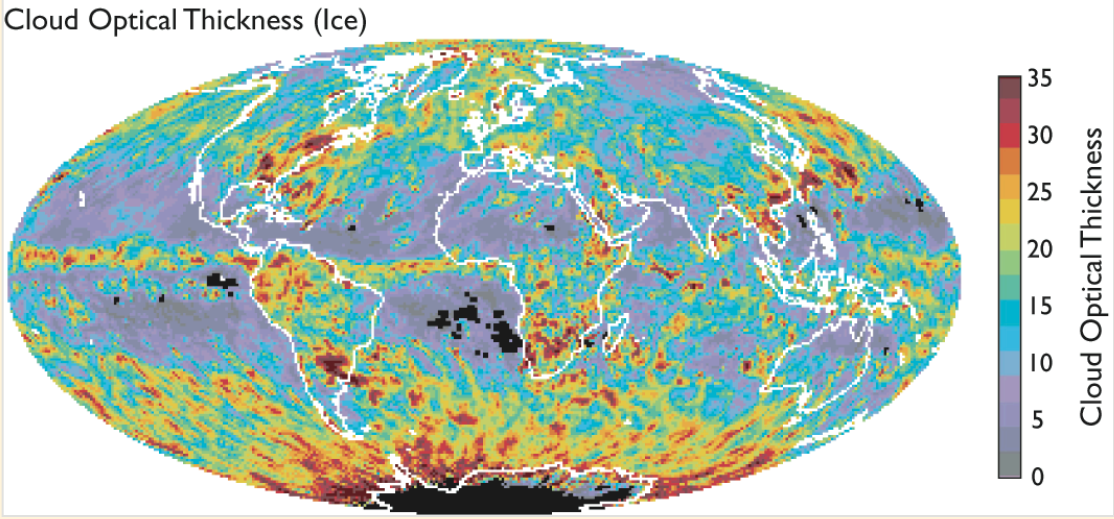
(M. D. King, S. Platnick et al. – NASA GSFC)

April 2005
Aqua C5 (QA mean)

Cloud_Optical_Thickness_Liquid_QA_Mean_Mean



Cloud_Optical_Thickness_Ice_QA_Mean_Mean

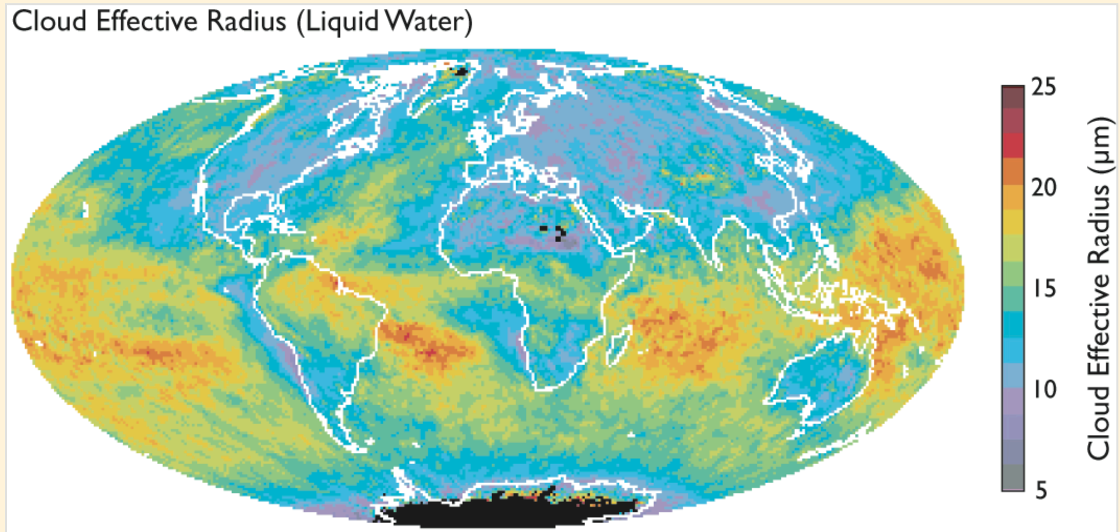


Monthly Mean Cloud Effective Radius

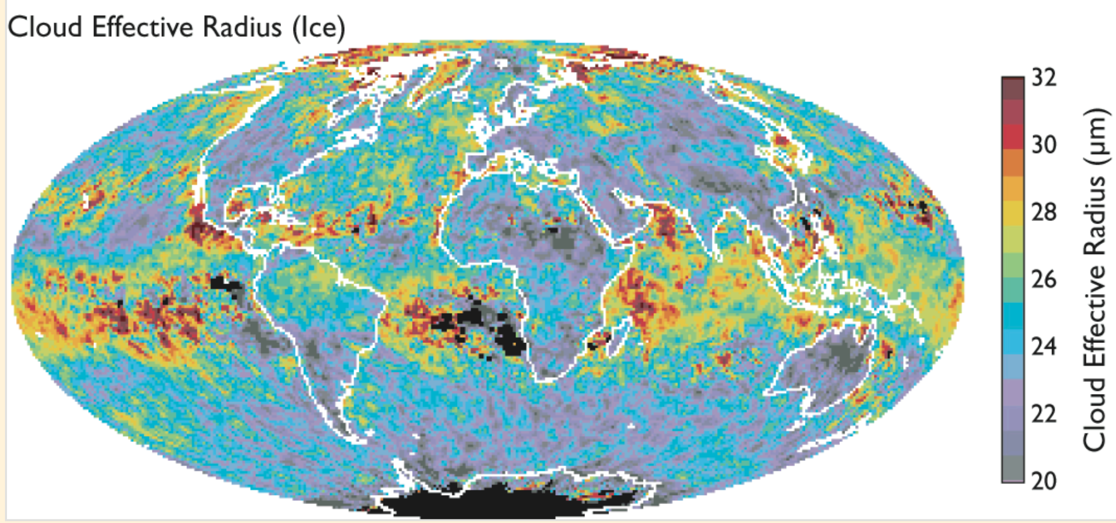
(M. D. King, S. Platnick et al. – NASA GSFC)

April 2005
Aqua C5 (QA mean)

Cloud_Effective_Radius_Liquid_QA_Mean_Mean



Cloud_Effective_Radius_Ice_QA_Mean_Mean

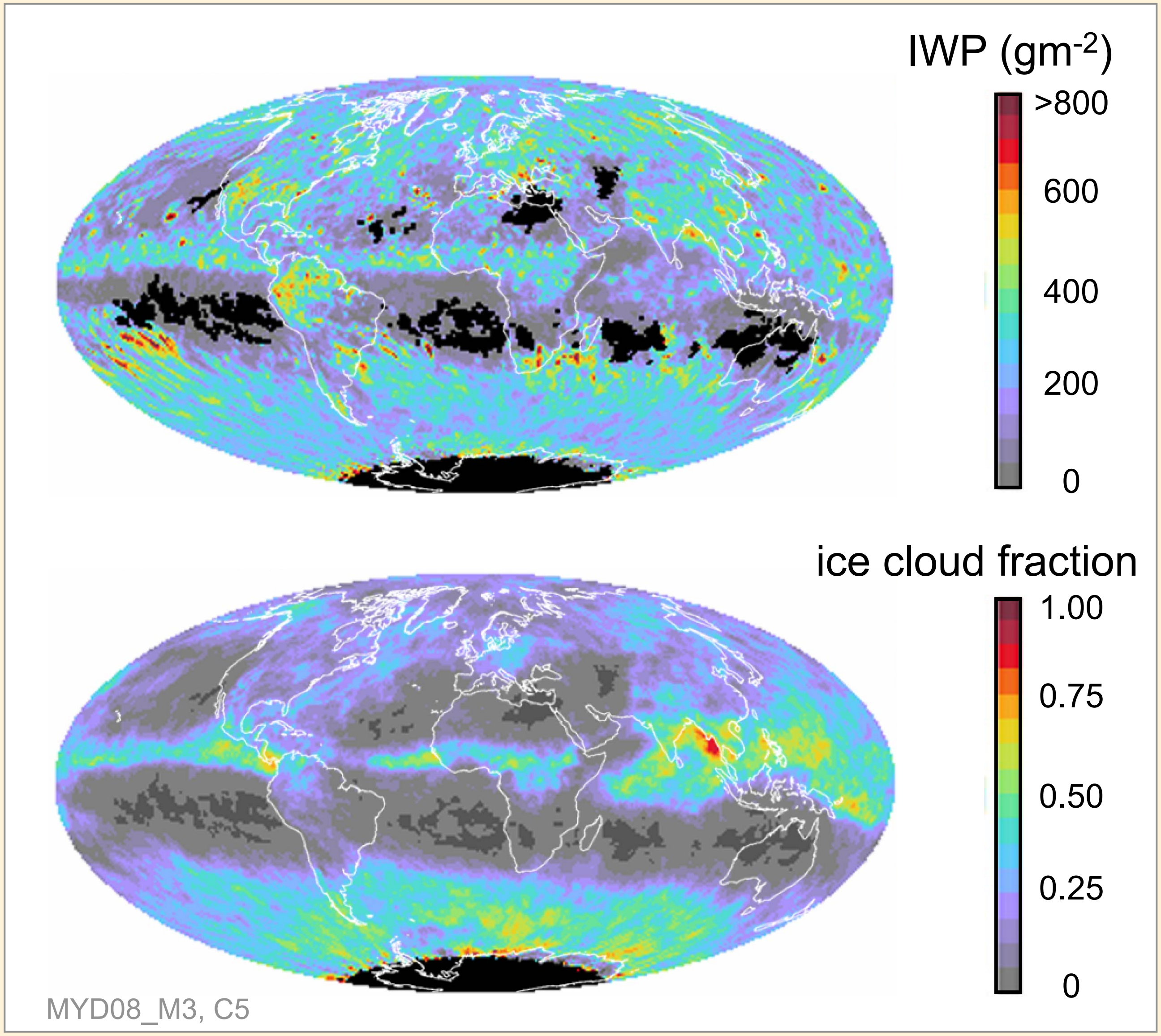


Monthly Mean IWP and Ice Cloud Fraction

Aqua, August 2006 (M. D. King, S. Platnick et al. – NASA GSFC)

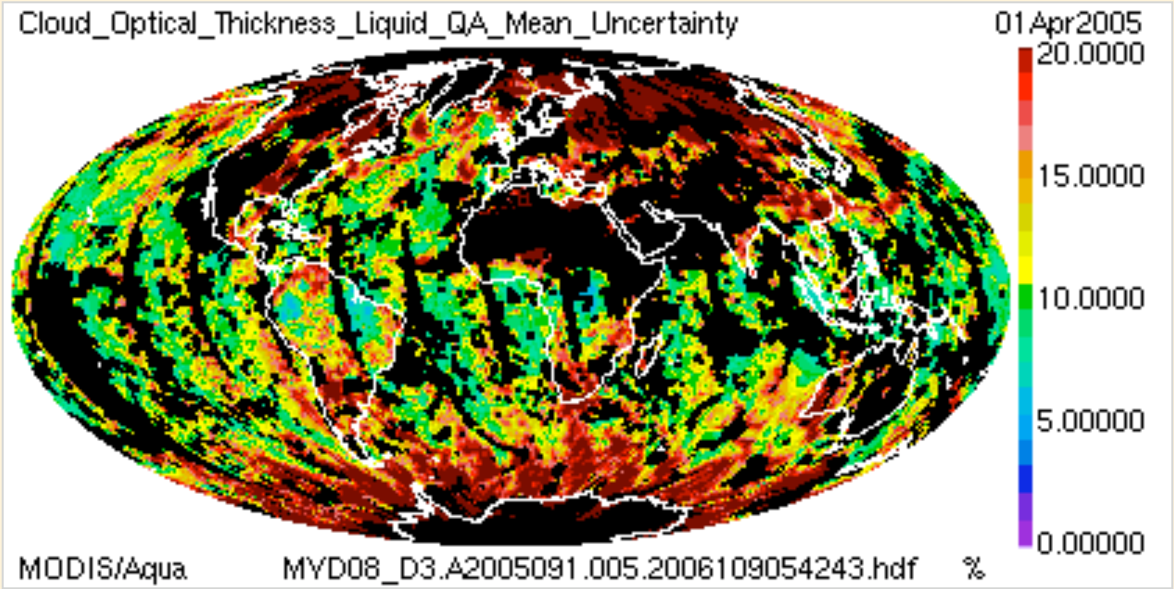
Cloud_Water_Path_Ice_QA_Mean_Mean

Cloud_Fraction_Ice_FMean

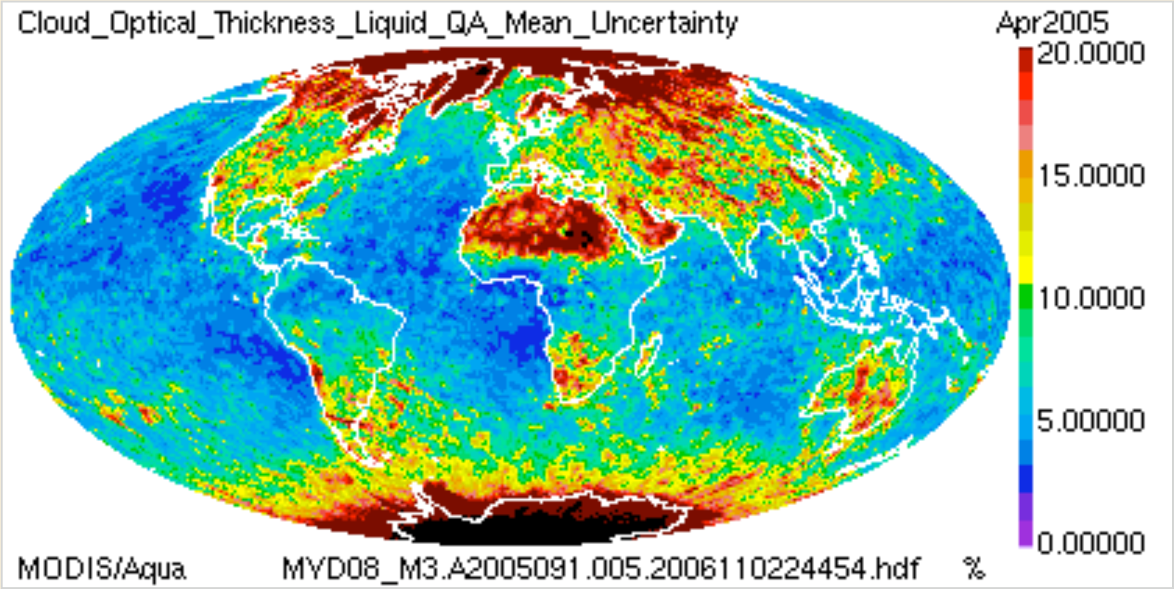


MODIS Aqua Collection 5, $\Delta\tau_c / \tau_c$ (%)

liquid water cloud
daily aggregation,
1 April 2005
(*assumption: correlation between pixels =1*)

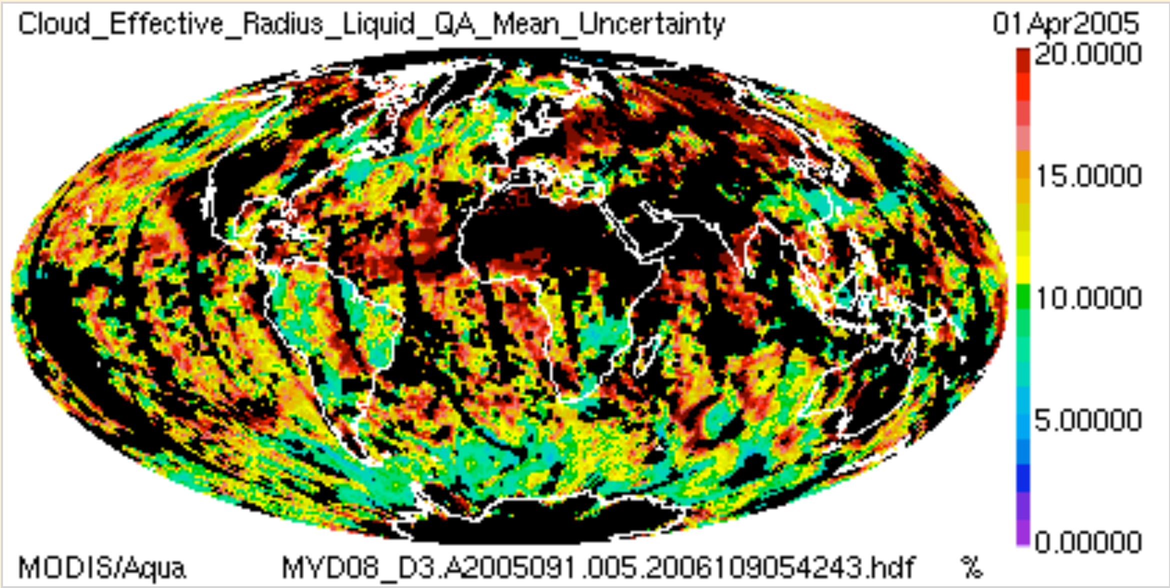


liquid water cloud
monthly aggregation,
April 2005
(*assumption: daily uncertainties uncorrelated*)

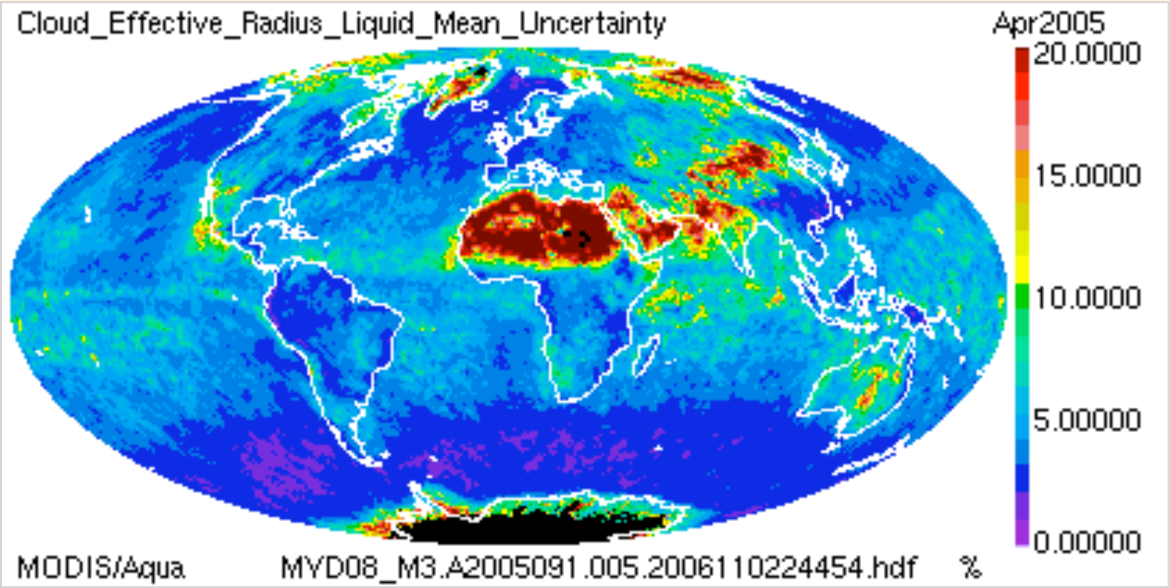


MODIS Aqua Collection 5, $\Delta r_e / r_e$ (%)

liquid water cloud
daily aggregation,
1 April 2005



liquid water cloud
monthly aggregation,
April 2005



MODIS Aqua Collection 5 Multilayer Cloud Flag, Monthly L3

Fraction of cloudy pixels (all phases) where the Multilayer Flag is set